Conceptual Design Report

Proton Plan 2

November 9, 2006

(*Updated:* 1/31/07**)**

Preface to PP2 CDR Addition to NOνA CDR

Proton Plan 2 (PP2) was originally a "campaign" as described in the attached Conceptual Design Report (CDR). With the merger of the NOνA Project and the PP2 campaign, items related to the neutrino program in general, rather than NOνA specifically, were moved off project. This is described in more detail in the section on Cost and Schedule (Section 3) of the PP2 CDR. The part of PP2 that is now in the NOνA Project will be called Accelerator and NuMI Upgrades (ANU), and appears as NOνA WBS 1.0 (R&D and Operating portion) and NOνA WBS 2.0 (MIE). The NOνA Technical Design Report (TDR) will appropriately cover the ANU portion of the NOνA Project.

Executive Summary

The future neutrino oscillation program at Fermilab [1] [2], devoted to long-baseline electron-neutrino appearance searches, will use the NuMI neutrino facility (NuMI--an acronym that stands for Neutrinos at the Main Injector). The NuMI facility produces a neutrino beam directed from Fermilab to northern Minnesota, over a baseline of about 800 km.

The NuMI line was commissioned in early 2005 for the MINOS neutrino oscillation experiment. A 120 GeV/c primary proton beam, single-turn extracted from the Main Injector, is focused onto a water-cooled graphite target. Downstream of the target are two parabolic horns that focus sign-selected secondary particles, which decay into neutrinos in an evacuated 675 m long decay pipe. Design values of the NuMI line are 4×10^{13} protons/pulse (ppp) every 1.9 s--corresponding to a beam power of 0.4 MW. The implementation of slip-stacking at the end of 2004 (to increase the anti-proton production rate for the Collider), together with NuMI turn-on, have pushed the total beam intensity in the Main Injector up to $\sim 3\times10^{13}$ protons/pulse. Presently the NuMI line is running at an average beam power of ~180 kW.

Proton Plan 1 is the current campaign of upgrades to maximize delivery of protons to the NuMI beam line as well as to the 8 GeV Booster Neutrino Beam (BNB), which currently serves the MiniBooNE experiment. The goal of Proton Plan 1 is to use a slip stacking technique to load protons into the Main Injector and ultimately deliver 320 kW of beam power to the NuMI beam line while still delivering protons for anti-proton production.

The NOνA experiment [2], the future electron-neutrino appearance program, will take place after the conclusion of the Collider program; it will require at least a factor 2 increase in beam power.

With the conclusion of the Collider program, several machines will become available to be used, in conjunction with the Booster and the Main Injector, to increase the beam power delivered to the NuMI facility. Proton Plan 2, consisting of upgrades and modifications to existing accelerator and beamline systems, has been developed to increase the proton rate to the NuMI neutrino line. This report focuses on the upgrades necessary to reach 700 kW beam power (Proton Plan 2), making use of the Recycler ring (currently an anti-proton storage ring) as a proton pre-injector to the Main Injector. This pre-injection removes the proton injection time from the Main Injector cycle time, and thereby enables the Main Injector to cycle as fast as allowed by magnets, power supplies and the RF system. Proton Plan 2 upgrades provide about a factor 2 increase in beam power, with only 10% increase in total beam intensity in the Recycler and Main Injector, by making full use of the maximum acceleration rate of the Main Injector. Modifications to the proton source and upgrades in the NuMI neutrino line to handle the higher beam power are both addressed in this report.

A separate plan, called Super NuMI or SNuMI (beyond 1 MW) is achieved by higher beam intensity, mostly in the Main Injector, due to the use of momentum stacking in the Accumulator, part of the present anti-proton source, and is not discussed but sometimes referenced in this report.

Proton Plan 2 upgrades achieve an 80% increase in proton throughput over Proton Plan 1 by moving the injection and the slipping portion of the slip-stacking process from the Main Injector to the Recycler, and otherwise maintaining the production process of Proton Plan 1. The various upgrades will now be briefly discussed.

For the Booster, the issue will be the need to increase proton throughput by 80% through an increased rate of pulses, close to what already has been achieved by Proton Plan 1.

The Recycler will be converted from an anti-proton to a proton storage ring, starting with the decommissioning all anti-proton specific devices, such as stochastic cooling tanks and electron cooling. A new injection line from the MI-8 proton line directly into the Recycler and a transfer line from the Recycler into the Main Injector are needed. The plan is to slip-stack six on six Booster proton batches in the Recycler, for a total intensity of 5×10^{13} protons/cycle, and, at the time they line up, extract them to the Main Injector in a single turn, where they will be recaptured and accelerated. A 53 MHz RF system needs to be added in the Recycler for beam injection and slip-stacking.

The Main Injector will have the slipping process offloaded to the Recycler, but will have to cycle faster and more often. The Main Injector cycle time will be reduced from 2.2 s to 1.333 s. In order to accommodate the faster ramp, two additional RF stations need to be installed.

The ability of the NuMI neutrino line to accept a 75% increase in power, over its design value of 400 kW, mainly involves improvements to the primary proton line to handle the faster repetition rate and new designs for the target and at least for the first of the two horn focusing systems. An upgrade of the present target pile air-cooling system is also required to cope with the larger beam power deposited in the target pile shielding. The acquired experience in running the NuMI line, which went through multiple failures and repairs of target and horns, also suggests the necessity of an upgrade of the Work Cell used to provide radiation shielding during the repair processes.

While most of the effort for the upgrades in the NuMI line is related to the higher beam power, the target and focusing horn configuration (neutrino beam optics) is also changed to meet the needs of the NOvA experiment. This means moving the target and the second horn to new locations within the target chase area in order to change the energy spectrum of the neutrinos to a higher energy (medium energy configuration).

Shielding assessments for all accelerators (Linac, Booster, Recycler and Main Injector) and for the NuMI neutrino line will need to be reviewed and revised as necessary to allow for the higher beam power. We do not foresee these requiring major financial resources.

The implementation of the Proton Plan 2 is planned to occur during two separate shutdown periods. The first shutdown period, of about 5.5 months, follows the completion of Collider Run II operations at the end of FY 2009. During this shutdown the modifications to the accelerator complex will be completed and the NuMI beamline will begin preparation for the 700 kW phase, but without changing the neutrino beam focusing optics. This allows the MINERvA (Main Injector ν-A interactions) experiment [3] to operate for about one year in the low energy neutrino configuration, presently used by the MINOS experiment. Since this requires the use of the existing target, the NuMI beamline will be capable of only ~400 kW of beam power, but at the same time it will be possible to commission all the modifications to the accelerator complex. In Spring 2011 a second shorter shutdown (~2 months) is planned to switch from the low energy to the medium energy neutrino configuration, replacing concurrently the target and the first horn. By then the NOνA experiment will have about a fourth of their detector (5kT) available for data taking.

We have constructed a detailed cost estimate for Proton Plan 2 including contingency for items that have not yet been fully designed. The estimated total cost is $33.4M in FY06 dollars ($20.3M M&S and $13.1M Labor) without overheads or contingency. The average contingency has been estimated to be 41%. Engineering effort is needed to further reduce uncertainties. Physicist labor costs are included in this estimate.

Proton Plan 2 has been designed for an annual integrated delivery of 6.0×10^{20} protons on target. More pessimistic parameters for operation suggest a lower limit of 4.6×10^{20} pot/yr.

Proton Plan 2 represents a technically feasible plan, which mainly relies on the reconfiguration of existing machines. By itself, Proton Plan 2 provides an 80% increase in beam power to the NuMI neutrino line over the present Proton Plan 1.

1. R. Plunkett, 'The Fermilab neutrino program', Nucl. Phys. Proc. Suppl. 155 (2006) 18, NuFACT05, June 2005.
2. D.S. Ayres et al., 'NOνA: Proposal to build a 30 kiloton off-axis detector to study νμ → νe oscillations in the NuMI beamline', FERMILAB-PROPOSAL-0929, Mar 2004.
3. The MinervA Collaboration, D. Drakoulakos et al., 'Proposal to perform a high-statistics neutrino scattering experiment using a fine-grained detector in the NuMI beam'.

1 Introduction

1.1 The present complex

A sketch of the Fermilab accelerator complex is shown in Figure 1.

The Booster is effectively the proton horsepower of the complex. Fed by 400 MeV H^- ions from the Linac, it accelerates protons to 8 GeV of kinetic energy at 15 Hz rate. Booster batches (typically up to $\sim5\times10^{12}$ protons) are transferred through the MI-8 line into the Main Injector (MI) or sent to the MiniBoone neutrino target.

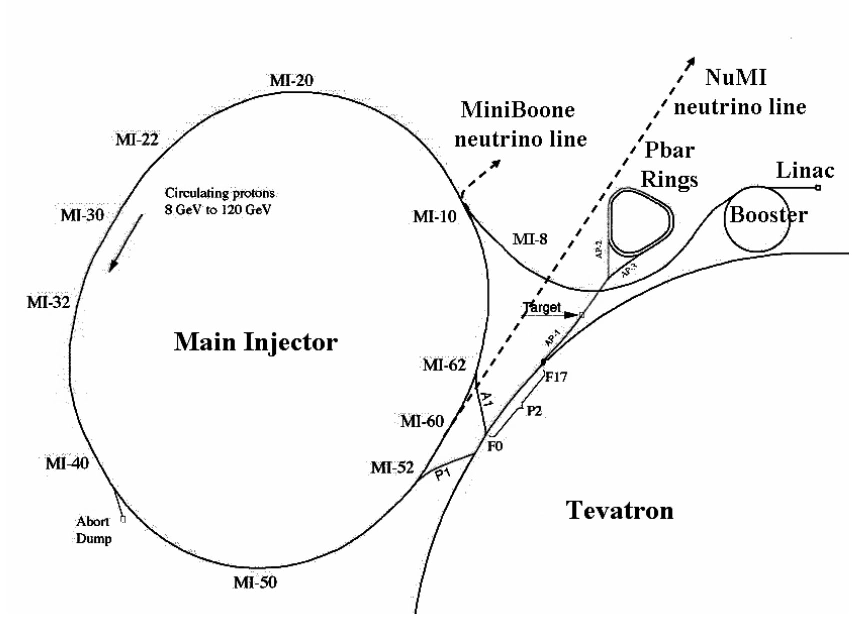


Figure 1: The Fermilab accelerator complex.

The Main injector is seven times the circumference of the Booster. Six Booster batches are required to fill up the machine, leaving one seventh of the circumference available for the rise-time of the extraction kicker. Table 1 summarizes the MI parameters.

Circumference (km)	3.319	Harmonic number	588
Injection momentum (GeV/c)	8.9	RF frequency at injection (MHz)	52.8
Extraction momentum (GeV/c)	120	RF frequency at extract. (MHz)	53.1
Transition gamma	21.8	Maximum RF voltage (MV)	4.3

Table 1: Parameters of the Main Injector.

The Main Injector is the central machine of the complex, equipped with a complex set of injection and extraction lines to connect to the other machines of the complex. It provides protons for anti-proton production, it has a dedicated extraction to the NuMI neutrino line and it is connected to the Tevatron for proton and anti-proton transfers.

An additional machine, the Recycler, is located in the Main Injector tunnel at a distance 57” above the MI ring and with the same basic cell geometry. The Recycler is a fixed 8 GeV kinetic energy antiproton storage ring, which makes use of permanent gradient and quadrupole magnets for the ring lattice. Antiproton transfers in and out of the Recycler Ring take place through two transfer lines connecting the Recycler to the Main Injector. Figure 2 shows the Main Injector tunnel in the MI-60 region, where the NuMI extraction is located.

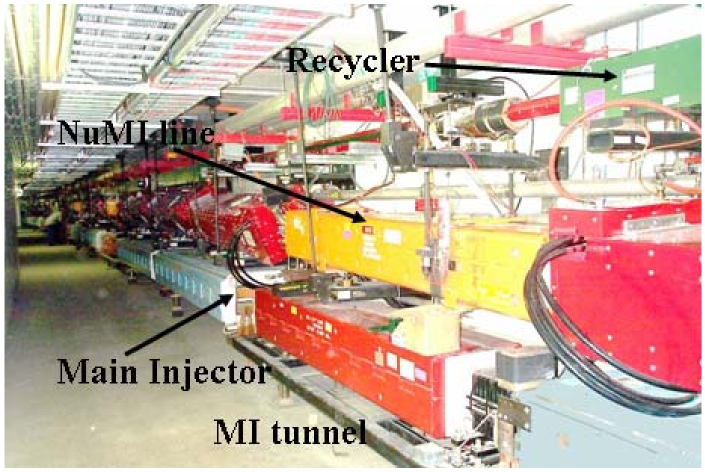


Figure 2: A photo of the Main Injector tunnel in the MI-60 region, showing the NuMI extraction line between the Main Injector at the bottom and the Recycler on top.

The NuMI Beamline line points from Fermilab to the MINOS detector installed in the Soudan mine, in Northern Minnesota, at a distance of 735 km from the neutrino target. A schematic of the NuMI line is shown in Figure 3.

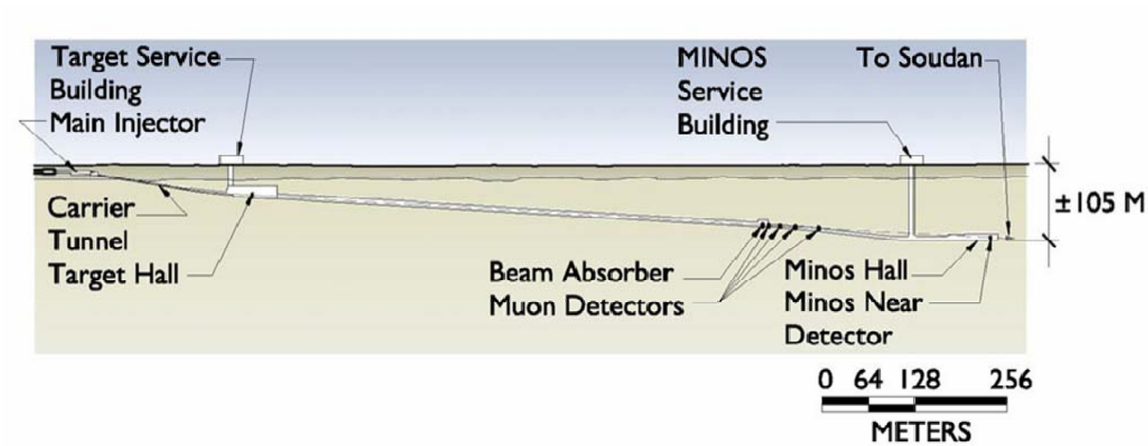


Figure 3: Schematic of the NuMI neutrino line. Protons are delivered from the Main Injector via the primary proton beamline through the carrier tunnel. The target and focusing horns are located in the target hall. The long section in the middle contains the decay pipe which is followed by the beam absorber, muon detectors, and near experimental hall.

The 120 GeV/c primary proton beam, single turn extracted from the Main Injector, is transported by a large acceptance primary proton line over a distance of 350 m, brought to a pitch angle of 58 mrad in order to point to the neutrino detector in the far location, and focused onto a water-cooled graphite target. Design values of the NuMI line are 4×10^{13} protons/pulse (ppp) every 1.9 s, corresponding to a power of 0.4 MW.

The graphite target, of 2 interaction lengths, is followed by two water-cooled, parabolic aluminum horns, pulsed with up to 200 kA, providing a 1/r toroidal field that has a maximum of 30 kG. The focused particles are allowed to decay in a 675 m long decay pipe of 1 m radius, evacuated down to 0.4 Torr. A water-cooled aluminum beam absorber is positioned at the end of the decay pipe.

High rate ionization chambers [4] are used to monitor the beam immediately upstream of the absorber (Hadron monitor) and in 3 successive alcoves downstream of the absorber (Muon monitors).

1.2 Present operating conditions

The Fermilab accelerator complex has recently seen substantial improvements in proton throughput. The short-baseline neutrino oscillation experiment MiniBoone has accumulated in the last few years 8×10^{20} protons from the Booster. In 2005 the Main Injector has started operation for the NuMI long-baseline neutrino facility, achieving a maximum delivered beam power of ~300 kW. The anti-proton source, part of the Tevatron Collider complex, has witnessed a steady increase in proton intensity. Up to 8×10^{12} protons/pulse (ppp) have been delivered on the anti-proton target by means of slip-stacking [7] two Booster batches in the Main Injector.

1.2.1 Accelerator operation

Currently the Main Injector has to satisfy simultaneously the needs of the Collider program and of NuMI operation. Two main cycles are operational in the Main Injector most of the time, ‘mixed-mode’ and ‘NuMI only’ cycles.

The default mode of operation is the ‘mixed mode’ cycle. Protons for the anti-proton target and for NuMI are simultaneously accelerated in the same cycle. Seven booster batches are injected into the Main Injector. The first two are slip-stacked together into a single batch for anti-proton production and then followed by five additional batches for NuMI. At 120 GeV/c flattop momentum, first the slip-stacked batch is extracted to the anti-proton target by means of a fast kicker, followed after ~1ms by a single turn extraction (~8 μs) of the five remaining batches to NuMI, for a total intensity of up to 2.5×10^{13} ppp.

Figure 4 shows beam intensity, RF acceleration curve, bunch length monitor and beam energy lost during a mixed-mode cycle. The seven steps in the beam intensity monitor correspond to the seven injected batches from the Booster at 15 Hz rate.

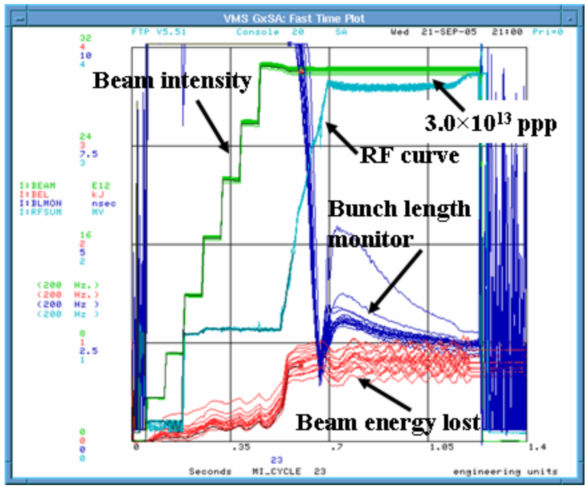


Figure 4: 'Mixed-mode' cycle in Main Injector

'NuMI only' cycles are run whenever the anti-proton source is not operational or when the spacing of the 'mixed mode' cycles is such to allow insertion of additional cycles. In this case the Main Injector is loaded with six Booster batches and all of them are extracted to NuMI in ~10 μs. In this mode a total intensity of 2.8×10^{13} ppp every 2 s has been achieved (see Figure 5), corresponding to a beam power of 270 kW.

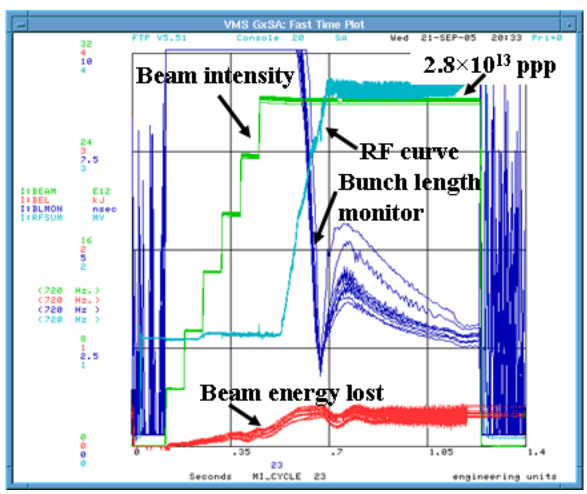


Figure 5: 'NuMI only' cycle in Main Injector

Recently NuMI only cycles have been implemented where the first one of the 6 batches is a slip-stacked batch, similarly to mixed-mode cycles. A maximum beam power of ~300 kW has been achieved. This represents the first step towards slip-stacking over multi-batches for NuMI.

The implementation of a transverse and longitudinal bunch-by-bunch digital damper system in the Main Injector has been essential to insure reliable running conditions at high intensities ($\geq 2\times10^{13}$ ppp) [8].

1.2.2 NuMI operation

NuMI operation is summarized in Figure 6, showing spill intensity, beam power and integrated protons on target versus time. A total of ~1.8×10^{20} protons have been collected on the NuMI target up to October 2006.

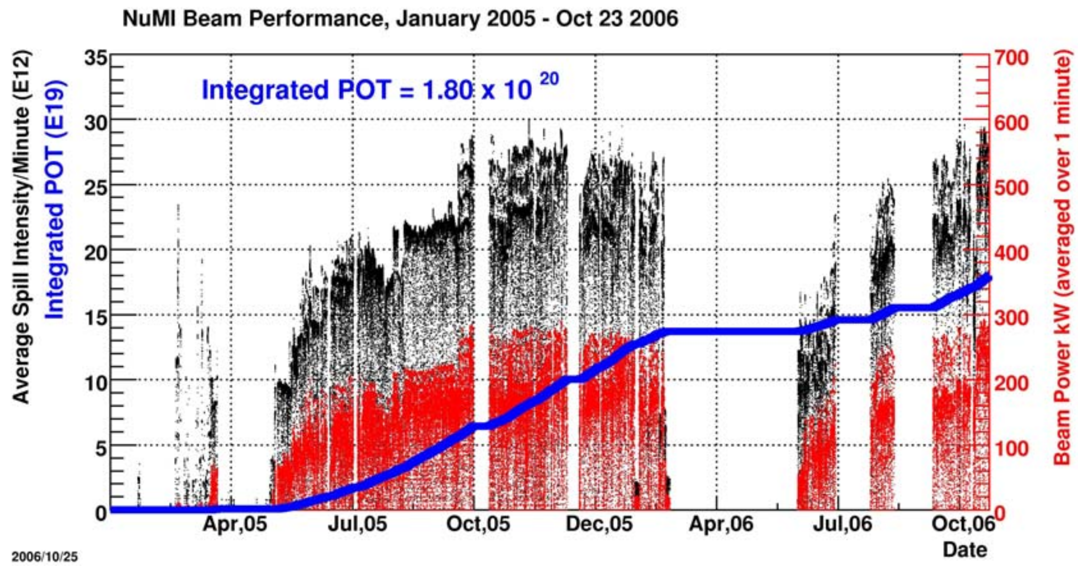


Figure 6: Spill intensity, beam power and integrated protons on target for NuMI operation.

An average beam power of ~180 kW has been achieved, with a peak power of 299 kW. The long interruption period from March to May '06 is due to a scheduled accelerator complex shutdown, while the other shorter periods are due to different failures of NuMI target hall components.

A 'beam permit system' has been set up to allow a reliable and safe operation at high beam power, where repeatedly misdirected beam could cause severe hardware damage. The beam permit is a complex system monitoring ~240 inputs from magnet power supplies, loss monitors, beam positions in front of the target, miscellaneous inputs like cooling water, vacuum valves, and 'beam quality' inputs from the Main Injector. In particular, several quantities are monitored in the Main Injector to insure a lossless extraction: no beam present in the position corresponding to the rise time of the extraction kicker, kicker current, beam positions in the extraction region and loss monitors during the ramp flattop.

The beam permit system will inhibit the current pulse if any of the quantities is out of tolerance at specified times, as close as few 100 μs to extraction. Anything failing the limits in the course of the extraction, i.e. fractional beam losses in the NuMI primary proton line larger than few 10^{-5}, will inhibit the following pulse. Moreover, in order to keep the primary proton line properly tuned, an 'auto-tune' program acting on the trim magnets of the line runs continuously to keep the beam within specified limits. In particular the beam positions on target are maintained within 125 μm. Fractional beam losses along the primary proton line have been kept well below 10^{-5} during operation [9].

4.Operation of the NuMI beam monitoring system,.MINOS Collaboration (Robert M. Zwaska et al.). Fermilab-Conf-06-090-Ad, Jun 2006. 8pp.

5. S. Kopp, 'The NuMI neutrino beam at Fermilab', FERMILAB-CONF-05-093-AD, PAC05, May 2005.
6. NuMI Technical Design Handbook, http://www-numi.fnal.gov/numwork/tdh/tdh_index.html
7. K. Seiya, 'Progress in slip-stacking and barrier RF', in proceedings of ICFA-HB2006, May 2006.
8. P. Adamson et al., 'Operational performance of a bunch by bunch digital damper in the Fermilab Main Injector', FERMILAB-CONF-05-145-AD, PAC05, May 2005.
9. R. Zwaska, 'Commissioning of the Fermilab NuMI neutrino beam', in proceedings of ICFA-HB2006, May 2006.

1.3 Planned Proton Plan 1 Upgrades

Proton Plan 1 [10] is a campaign of upgrades to maximize delivery of protons to the NuMI beam line, which currently serves the MINOS experiment, as well as the 8 GeV Booster Neutrino Beam (BNB), which currently serves the MiniBooNE experiment. Proton Plan 2 implicitly assumes that Proton Plan 1 has been completed and has been reasonably successful in achieving its goals.

Proton Plan 1 was first formalized on late 2004, and incorporated many ongoing activities. It was officially baselined in September of 2005, and since then all activities have been carefully tracked and change controls have been implemented.

Proton Plan 1 is concurrent with Run II (the second run of the Collider program). The current timeline has the final associated hardware improvements installed in the summer 2008 shutdown, and all benefits realized by mid 2009, at which point, it will be fully superseded by Proton Plan 2.

The goal of Proton Plan 1 is to use a slip stacking technique to load protons into the Main Injector and ultimately deliver approximately 400 kW of beam power to the NuMI beam line while still delivering protons for antiproton production. By increasing the total proton output from the Booster, it is planned to continue delivering protons to the 8 GeV beam line (currently the MiniBooNE experiment) at a level of roughly $(1 \sim 2)\times 10^{20}$ per year.

Broadly speaking, Proton Plan 1 elements fall into four categories:

1. Increasing the maximum Booster repetition rate from the 7.5 Hz to roughly 9 Hz
2. Increasing Booster efficiency so that more beam may be accelerated while keeping the total beam loss in the Booster tunnel at a constant level. Operationally, beam loss has been the limiting factor for Booster throughput, and will likely continue to be for some time.
3. A number of hardware and operational issues to implement slip stacked operation in the Main Injector
4. Some projects aimed at increased reliability and stability, particularly in the Linac.

Table 2 shows the significant elements of Proton Plan 1, broken down by machine, and includes the status of the major projects. At the time of this writing (10/2006), Proton Plan 1 is approximately 50% complete in terms of total resources. The most significant remaining projects are:

1. **Booster Corrector Upgrade –** This is an ambitious project to replace the 48 corrector elements in the Booster with dramatically improved versions. This system is probably not necessary to run NuMI alone, even with slip stacking; however, it will probably be necessary to reduce Booster losses enough to allow the operation of the 8 GeV program during the NuMI slip stacking era. Half of the Booster correctors are scheduled to be installed in the 2007 shutdown and the remainder of the system in the 2008 shutdown.
2. **Main Injector Collimation System** – This is a two stage collimation system that will be required to keep beam loss in the Main Injector at an acceptable level during slip stacked operation to NuMI. It is scheduled to be installed during the 2007 shutdown.
3. **Main Injector RF Upgrade –** This is a set of improvements to the Main Injector RF system that will be required for stable slip stacked operation. These are scheduled to be completed during the 2007 shutdown.

Machine	Project	Status
Linac	Stockpile a two year supply of 200 MHz power amplifier tubes (7835's)	Complete
	Characterize and improve 200 MHz lower level RF	Ongoing
Booster	Replace and reconfigure injection bump (ORBUMP) System	Complete
	Relocate 8 GeV dump from Booster to MI-8 line	Complete
	Make Booster robust to 9Hz average repetition rate	Complete
	Design, build and install new corrector system	Ongoing
Main Injector	Replace seven quadrupoles with large aperture versions, to reduce injection and extraction losses	Complete
	Develop multi-batch and multi-batch slip stacked operation	Ongoing
	Design and install collimation system, both the MI-8 transfer line and in the Main Injector Ring	MI-8 Complete Ring Ongoing
	Modify injection kicker to allow rates for multi-batch slip stacked operation	Complete
	Characterize RF system and make improvements necessary for slip stacked NuMI operation	Ongoing

Table 2: Major elements of Proton Plan 1

As far as proton delivery goes, we are presently delivering five Booster batches to NuMI every Main Injector cycle, along with 2 slip stacked batches to antiproton production. This will continue until the 2007 shutdown, after which we will be able to begin multi-batch slip stacking, sending two batches to antiproton production and nine to NuMI. Improvements in the Booster will allow us to continue to deliver beam to the 8 GeV program as the NuMI intensity ramps up. The remainder of the Booster correctors will be installed in the 2008 shutdown, which will effectively end the hardware activities in Proton Plan 1. An additional year of "tuning" is included in the plan time line to take full advantage of the improvements which have been made. The Proton Plan 1 analysis projects that at the end of this time, losses in the Booster will be reduced to the point that a maximum of 1.85E17 protons/hr could be accelerated.

The ultimate design goal for the plan is to deliver nine Booster batches of 4.1×10^{12} protons (at extraction) to the NuMI line every 2.2 seconds for a total of 320 kW. This number will automatically increase to 390 kW at the end of the collider program, when all 11 slip stacked batches will be available to NuMI (see Table 3 in Section 1.4 for a summary of design parameters in Proton Plan 1).

1.3.1 References

10. The web page is http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml.

1.4 Proton Plan 2

A rise in beam power to NuMI is anticipated with the conclusion of the Collider program. The operation of the Main Injector would be largely simplified at that point and NuMI would naturally gain the portion of beam presently delivered to the anti-proton production target.

Substantial additional gains are possible through a reconfiguration of the present accelerator complex and an upgrade of the Main Injector RF system.

Proton Plan 2 reuses the Recycler ring as a proton pre-injector to the Main Injector. Proton Plan 1 foresees operation of the Main Injector with a cycle of 2.2 s, of which about 30% is spent waiting for batch injections from the Booster. It has been proposed [11] to use the Recycler ring as a proton pre-injector, accumulating proton batches from the Booster while the Main Injector is accelerating beam.

Construction of a short transfer line between the MI-8 line and the Recycler ring, together with an extraction line from the Recycler into the Main Injector is necessary to make the Recycler a proton pre-injector to the Main Injector. The Main Injector would then cycle as fast as allowed by magnets, power supplies and RF system. The 120 GeV cycle time could be reduced to 1.47 s by eliminating the beam loading time.

The other main factor affecting the Main Injector cycle length is the acceleration rate. Magnets and power supplies of the Main Injector have been designed for a maximum rate of 240 GeV/s. The present RF system, consisting of 18 stations, retrieved from the decommissioned Main Ring, has enough power to stably accelerate up to $\sim6\times10^{13}$ ppp at a rate of 205 GeV/s [12]. The system is presently operated in this mode. The addition of two RF cavities in the Main Injector ring, from the three available spares, would allow operation at the maximum acceleration rate of 240 GeV/s [12] and hence reduce the Main Injector cycle time to 1.33 s; an additional gain of ~10%.

Additionally, the momentum acceptance of the Recycler is sufficiently large (1.5% full span) to allow slip-stacking of Booster batches. The plan is to slip-stack six on six batches, and, at the time they line up, extract them to the Main Injector in a single turn, where they would be recaptured and accelerated. A 53 MHz RF system needs to be added in the Recycler to perform this slip-stacking.

Design parameters for Proton Plan 2, together with Proton Plan 1 parameters, are shown in Table 3. In summary, Proton Plan 2 provides about a factor 2 increase in beam power with only 10% increase in total beam intensity, by making full use of the maximum acceleration rate of the Main Injector.

	Proton Plan 1	Proton Plan 2	
Booster			
Extracted Batch Intensity	4.3E+12	4.3E+12	protons
Average Pulse Rate	5.9	10.5	Hz
Average Beam Rate	5.0	9.0	Hz
Norm. Trans. Emittance at Extr.	15	15	π·mm·mrad @ 95%
Long. Emittance per Bunch at Extr.	0.08	0.08	eV·sec @ 95%
δp (After Bunch Rotation)	8	8	(±) MeV/c @ 95%
Recycler Ring			
Number of Injections		12	injections
Total Beam Injected		5.16E+13	protons
Injection Kinetic Energy		8	GeV
Injection RF Frequency		52.809	MHz
RF Frequency Difference		1260	Hz
Extraction RF Frequency		52.809	MHz
δp at Extraction		19	(±) MeV/c @ 95%
Main Injector			
Number of Injections	11	1	injections
Cycle Time	2.2	1.333	s
Beam Momentum at Extraction	120	120	GeV/c
Beam Intensity at Extraction	4.5E+13	4.9E+13	protons
Norm. Trans. Emittance at Extr.	20	18	π·mm·mrad @ 95%
Long. Emittance per Bunch at Extr.	0.4	0.4	eV·s @ 95%
δp/p at Extraction	8.E-04	8.E-04	(±) @ 95%
MI/RR Tunnel Losses			
8 GeV Beam Efficiency	95%	95%	
Controlled 8 GeV Loss to Abort	0.0%	2.1%	
Controlled 8 GeV Loss to Collimators	2.5%	1.1%	
Uncontrolled 8 GeV Losses	2.5%	1.7%	
Transition Losses (Upper Bound)	0.2%	0.2%	
Power Deposited in Abort	0	1060	W
Power Deposited in Collimators	682	558	W
Distributed Uncontrolled Loss	0.25	0.34	W/m
NuMI			
Maximum Proportional Loss in Carrier Pipe	1.0E-05	5.7E-06	
Spot Size on Target	1.1	1.3	mm (RMS)
Max. Beam Intens. on NuMI Target	4.5E+13	4.9E+13	protons
Max. Beam Power on NuMI Target	392	705	kW
Protons per Hour	7.3E+16	1.3E+17	protons/hr.

Table 3: Summary of design parameters for Proton Plan 1 & 2.

1.4.1 Operating scenarios

Table 4 compares the present operating scenarios with multi-batch slip-stacking in the Main Injector for NuMI (Proton Plan 1) and with the set of scenarios made possible by reconfiguring the accelerator complex after the conclusion of the Collider program.

	Present operating conditions	**Proton Plan 1** **Multi-batch slip-stacking in MI**	**Proton Plan 2** **Multi-batch slip-stacking in Recycler**
Booster intensity (protons/batch)	$4.3\text{-}4.5\times10^{12}$	4.3×10^{12}	4.3×10^{12}
No. Booster batches	7	11	12
MI cycle time (s)	2	2.2	1.333
MI intensity (ppp)	3.1×10^{13}	4.5×10^{13}	4.9×10^{13}
To anti-proton source (ppp)	8.2×10^{12}	8.2×10^{12}	0
To NuMI (ppp)	2.25×10^{13}	3.7×10^{13}	4.9×10^{13}
NuMI beam power (kW)	210	320	700
MI Protons/hr	5.5×10^{16}	7.3×10^{16}	1.3×10^{17}

Table 4: Present and foreseen operating scenarios. The first two columns show NuMI intensities and beam power values for mixed-mode cycles in the Main Injector.

11. S. Nagaitsev, E. Prebys, M. Syphers, ‘First report of the Proton Plan study group’, Fermilab Beams-doc-2178, Feb. 2006.
12. I. Kourbanis, ‘Beam acceleration capabilities of the present MI RF system’, Fermilab Beams-doc-1927, Aug. 2005.
13. D. McGinnis, ‘A 2 MW multi-stage proton accumulator’, Fermilab Beams-doc-1782, Nov. 2005.

1.5 Beam Physics

1.5.1 Introduction

Proton Plan 2 achieves an 80% increase in proton throughput over Proton Plan 1[1] [14] by moving the slipping portion of the injection and slip-stacking processes from the Main Injector to the Recycler, otherwise maintaining the production process of Proton Plan 1. For the Booster, the additional issue will be the need to increase throughput by 80% through an increased rate of pulses (this rate should be achieved by Proton Plan 1). The Main Injector will have the slipping process offloaded to the Recycler, but will have to

[1] The Proton Plan Design Handbook is found on its webpage: http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.shtml. A public site viewable outside Fermilab is: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml.

cycle faster and more often. The Recycler was not built to store high-intensity proton beams, but the similarity of its lattice and aperture with the Main Injector make it capable of doing so; the beam dynamics within the Recycler will be similar to those in the Main Injector.

1.5.2 Overview of the Beam Cycle

The Proton Plan 2 Recycler cycle involves stacking 12 batches of 8 GeV booster beam in the Recycler, accelerating the beam in the Main Injector, and extracting the beam to NuMI. An approximate timeline is shown in Figure 7 and is described in this section.

The Linac and Booster will accelerate beam on 12 successive cycles spaced at 15 Hz (67 ms). Such operation is presently typical for the Proton Source. The Linac beam will provide its typical beam: debunched 200 MHz bunches at 400 MeV and intensity of ~ 10^9 H^- ions per bunch, with ~ 20 μs pulse length.

The Booster will accumulate the Linac beam and accelerate it to 8 GeV. The extracted beam will be bunched at 53 MHz and have an intensity of 4-5×10^{12} protons per batch (~82 bunches). On every Booster cycle, the Booster must rebunch the beam from the Linac and accelerate it through transition; beam loss is experienced early in the cycle after debunching and at transition. Furthermore, to support the slip-stacking operation the beam must be notched, cogged, bunch-rotated, and phase-locked to the Recycler. These four processes are presently performed in the Booster, but each has some inefficiency; they will be further addressed in the Booster section. The extracted beam will likely use the MI-8 collimators (installed as part of the Proton Plan 1) to reduce the tails of the momentum distribution.

Each Booster batch will be injected to a particular location on the Recycler azimuth with respect to the beam already circulating[2]; the batches are injected every 1/15 s. The first six batches are injected such that they lie adjacent to each other, within the limitations set by the injection kicker[3]. The Recycler 53 MHz RF will be active to keep the beam bunched, using about 100 kV; whether one or two frequencies will have voltage will depend on the optimized details of slip-stacking. After the sixth injection, the six revolving batches must be accelerated or decelerated to a different orbit. The Recycler, being seven times the circumference of the Booster, would then have one additional slot for further injections[4]. Beam is then injected six more times into that gap; the momentum difference induces slipping which moves the newly injected beam out of the gap in the time between injections. Two RF frequencies will be used to keep each of the beams bunched. After the final batch is injected the beams slip again for 1/15 s, reestablishing the gap for extraction.

The Recycler beam is extracted in a single-turn into stationary 53 MHz RF buckets in the Main Injector, for a total intensity of about 5×10^{13} protons. The twelve batches being

---

[2] The first batch is not sent to a particular location as there is no beam already circulating in the Recycler.

[3] We expect that there will be two vacant buckets between 82-bunch batches.

[4] This assumes that the injection kicker has sufficiently short rise and fall times to fit in the seventh batch. If the kicker is not fast enough, a double-length slot must be made by injecting only five batches before slipping, reducing the total beam power to NuMI by 8%.

merged into six, the Main Injector will have charge in about 500 of its 588 buckets. The buckets are sized to each contain two slip-stacked bunches[5] using about 1 MV/turn among the 20 cavities. The beam is accelerated and collimated as in Proton Plan 1, except that the ramp rate of the magnets will be increased to 240 GeV/s (from 205), and an additional two RF cavities will increase the ring voltage by 11%. Extraction will occur in a single turn, sending the entire beam to the NuMI beamline; this extraction is presently in place for NuMI operation.

The NuMI primary line optics will remain the same as the original design, except that the final focus may be changed to enlarge the beam size on target for survivability[6]. However, the line will need to operate at an increased rate from its design, forcing some changes in magnets and power supplies. Target hall components will have to deal with greater average power deposition, though the intensity per pulse will be the same as in Proton Plan 1.

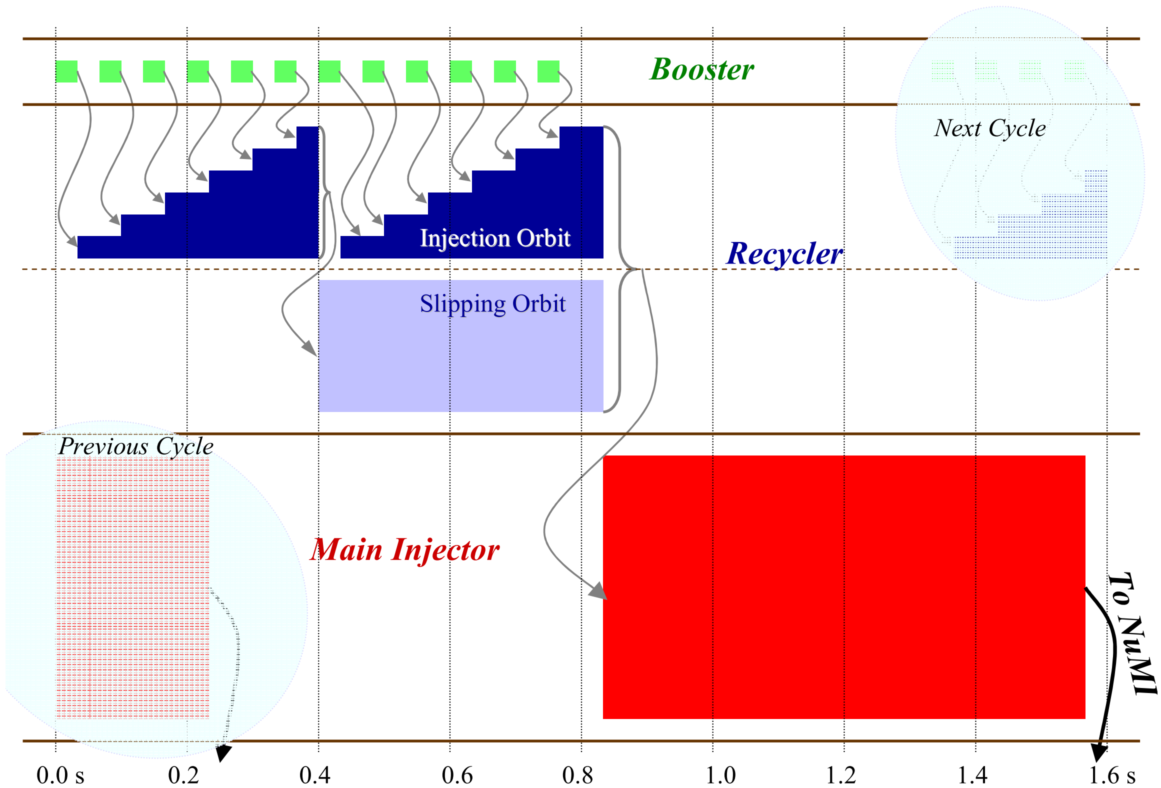


Figure 7: A diagram of the timeline for the slip-stacking process. The vertical height of each bar is proportional to the amount of beam. The zero is set arbitrarily at the time of first injection the Booster; an operational timeline will likely start earlier.

---

[5] The two bunches are separated by momentum, but not azimuth.

[6] The present spot size is typically 0.8-1.2 mm RMS in both transverse directions. The larger beam sizes are correlated with higher intensities. The design of the primary beamline allows the spot size to be tuned by a simple adjustment of the last few quadrupole magnets.

1.5.3 Overview of Slip Stacking

Slip stacking is a set of RF manipulations which merges two sets of bunched beam into one, doubling the bunch intensity (or conversely halving the azimuth used for the two beams). The distinguishing component of slip stacking is the use of two RF systems with slightly different frequencies; the RF is used to keep two separate bunch trains bunched, while being at different energy from each other and thus having different revolution frequencies. The RF voltages are just high enough to keep the beams bunched, but low enough to allow the two beams to slip past each other. When the two are coincident in azimuth (separated in energy), a significantly more powerful RF system is turned on. The third system operates at the mean of the two initial frequencies and is powerful enough to keep beam contained in its large amplitude RF buckets, preventing further slippage. Compared to other stacking procedures, the advantage of slip stacking is that it occurs quickly, because it does not require debunching, rebunching, or other slow processes.

The procedure of slip stacking was first developed and demonstrated at CERN [15], but the gains were not sufficient to offset the increased losses in the CERN PS or SPS; so slip stacking was never used in regular operation at CERN. At Fermilab, slip stacking was proposed in the Main Injector as part of the Run II luminosity upgrades[7] [16], where it would improve antiproton production rates by increasing the number of protons delivered to the antiproton target. A scheme was developed through which the Main Injector could support slip stacking for antiproton production, while also providing (unstacked) beam to NuMI. This mode of operation has been in place since 2004 [17] and typically provides batch intensities of 8×10^{12} protons, concurrent with an additional 22×10^{12} of unstacked beam for neutrino production.

Slip stacking, as operational in the Main Injector, combines two Booster batches into one for antiproton production. Typically, an additional five batches are injected after the initial two, but are not slipped – these do not directly affect the slipping process. To accommodate slipping, two RF systems change between four different RF frequencies: $\{f_0 - \Delta f, f_0 - \Delta f/2, f_0, f_0 + \Delta f/2\}$. f_0 = 52.8114 MHz is the Main Injector injection frequency; $\Delta f \approx$ 1400 Hz is the frequency separation between the beams at injection and capture.

As shown in Figure 8, the beam is injected into the first RF's buckets at f_0, and then decelerated to $f_0 - \Delta f$. 1/15 s after the first injection, the second batch is injected into the second RF at f_0. In a sequence that maintains a minimum frequency difference[8], the frequencies of the two beams are adjusted so that they finish at $f_0 \pm \Delta f/2$ and the time integral of Δf between the second injection and capture must equal the azimuthal separation of the batches at the second injection. In the sequence shown in Figure 8 the frequency difference is modulated, reaching a maximum near 2 kHz, leading to an

[7] The Run II project homepage is http://www-ad.fnal.gov/run2upgrade/. Slip stacking was an addition to the original Run II designs.

[8] A minimal criterion for stability is that $\alpha = \Delta f / f_s \geq 4$, where f_s is the synchrotron frequency of the beam under the influence of a single RF system. For a typical voltage of 100 kV/turn f_s =280 Hz, and scales with the square root of voltage. For details, see. Boussard and Mizumachi [15] or the F. E. Mills reference [18].

integral of around 130 buckets. The batch length is only 84 buckets; the greater initial separation minimizes interference of the injection with beam leeched from the first batch due to the two RF frequencies. Some of the freedoms in choosing the above parameters are reduced when slipping more than two batches, as in the Proton Plans 1 & 2.

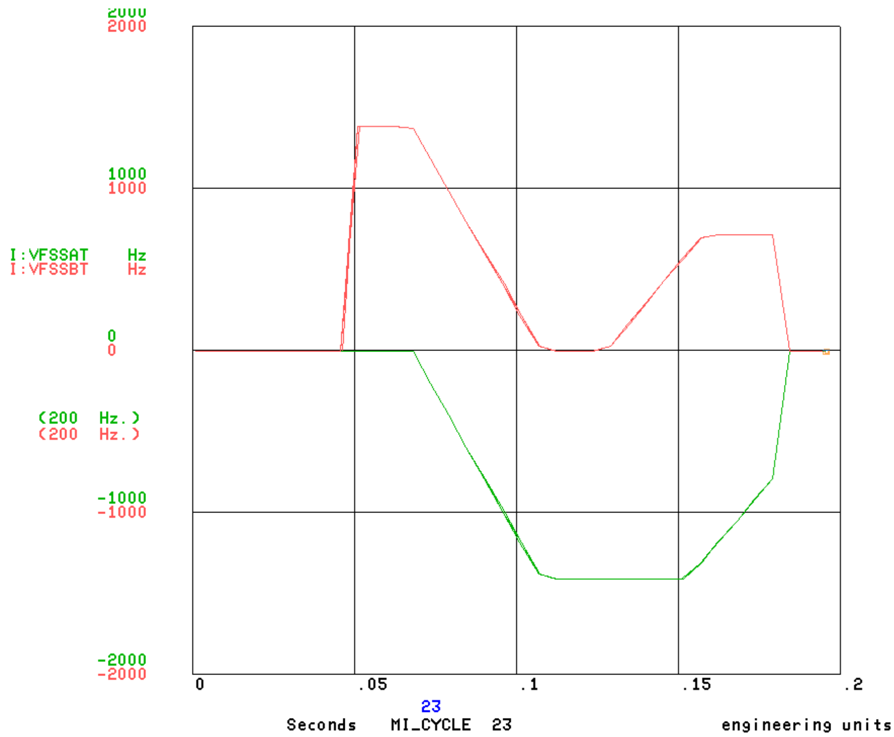


Figure 8: Operational frequency curves for two-batch slip stacking. Beam is injected on the central frequency (0 Hz) at ~ 0.06 and 0.12 s. The frequencies of the two beams are adjusted (also changing the energy) until they slip fully and bracket the central frequency, at which time they are captured (0.18 s).

Proton Plan 1 will extend slip stacking to NuMI by injecting 11 batches of beam into the Main Injector: two for antiproton production and nine for neutrino production. These batches will be injected in groups of 5 and 6, and then slipped together. The procedure is conceptually similar to two-batch stacking and is illustrated in Figure 9 and Figure 10. The obvious difference in the procedure is that more injections take place (5 on the first RF, 6 on the second) and the process takes longer. Additionally, the frequency difference is constrained to be the spacing between batches, which is nominally 84 buckets. So, $\Delta f = 84 \times 15 = 1260$ Hz and cannot be significantly modulated. This constraint limits the voltage that can be applied to the two RFs and will also apply for Proton Plan 2.

To produce the two azimuthally separated bunch trains for antiproton and neutrino production (as shown in Figure 9), only 11 batches can be injected into the Main Injector, while it could in principle hold 12 and preserve a single abort gap. This is shown in sequence 6 of Figure 9, where the last batch is displaced an additional 42 buckets. Allowing for the slippage of the additional gap requires an additional 1/30th second. Additionally, the fall time of the 8 GeV injection kicker is slow enough that several bunches of beam are kicked out of the machine. A similar loss will occur if 12-batch injection is attempted for NuMI. To control this loss Proton Plan 2 will need faster injection kickers.

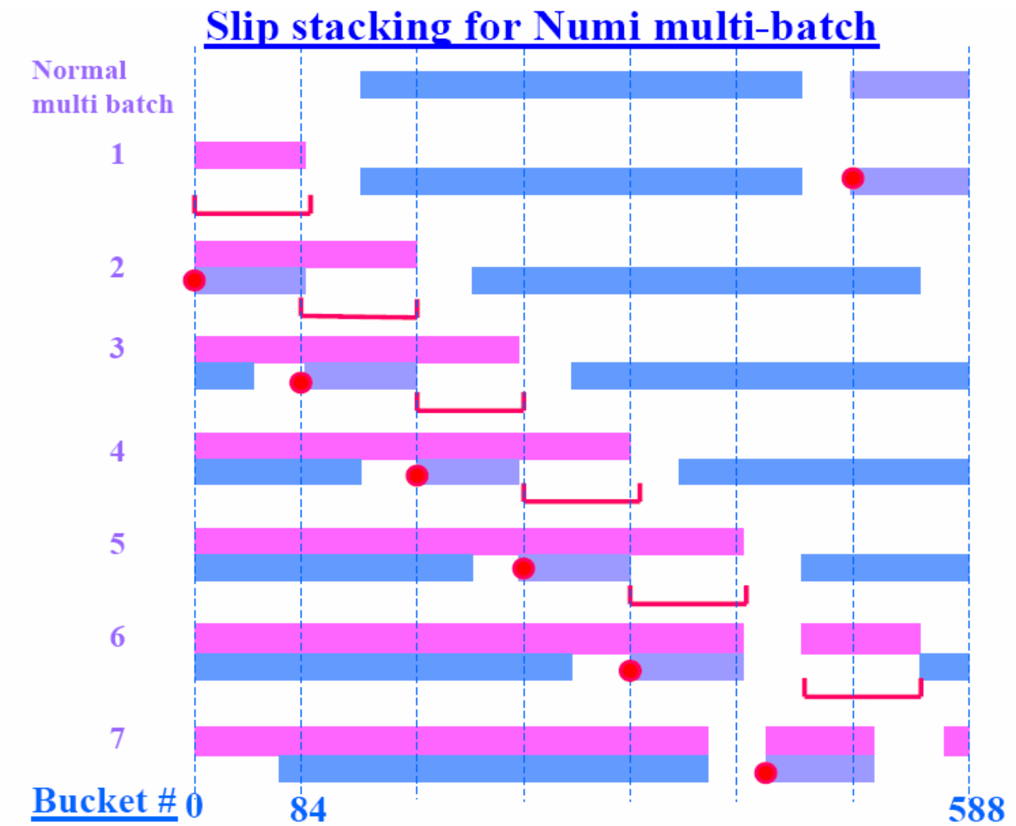


Figure 9: Illustration of batch positions at various times throughout the slipping process of Proton Plan 1. The blue bars show the position of beam on a slipping orbit, i.e. slipping relative to injected beam. Sequences 1-6 indicate the last 6 injections, each injection indicated by a red bracket. Sequence 7 shows the position of the beams at the time of recapture.

There are several disadvantages or issues related to slip stacking in the Main Injector. The process always dilutes longitudinal emittance, even under ideal circumstances. The dilution occurs because the bunches must be separated in energy, but combined into a single bucket. The interior area is then filled by filamentation. The total longitudinal phase space is increase by at least 50% (over the sum of the initial two). Furthermore, longitudinal emittance is minimized by maintaining a lower RF capture voltage, but that leads to slippage of the uncaptured tails, which contribute to losses elsewhere. In typical operation, the longitudinal emittance of slipped beam is ~ 80% greater than the combined emittances of the original beams.

Another issue is that the RF manipulations make use of a large portion of the momentum aperture. The beam centroids are moved from $f_0 - \Delta f$ to $f_0 + \Delta f / 2$. Additionally, the momentum distribution of the beam contributes. The total used aperture is then: $3\Delta f / 2 + 2 f_0 \eta \delta p / p$, which is 2700 Hz or 52 MeV. While this usage is large, the Main Injector and Recycler apertures are adequate.

Beam loading in the Main Injector RF cavities has long been recognized as a possible limitation to slip stacking performance [19]. The induced transient voltages on the main RF cavities could only be controlled through an aggressive system of beam loading compensation using both feedback and feedforward loops [20]. Even when compensation allows acceleration of beam to the production target, there are always increased losses with beam current. The dominant effect is that beam is not properly contained within the slipping buckets [21]. Those particles are then moved to higher amplitude along the separatrices. If the particles are not immediately lost they can then slip to an empty area of the ring and be lost at injection, extraction, or during acceleration. Proton Plan 2 will have to mitigate these losses through several methods described below.

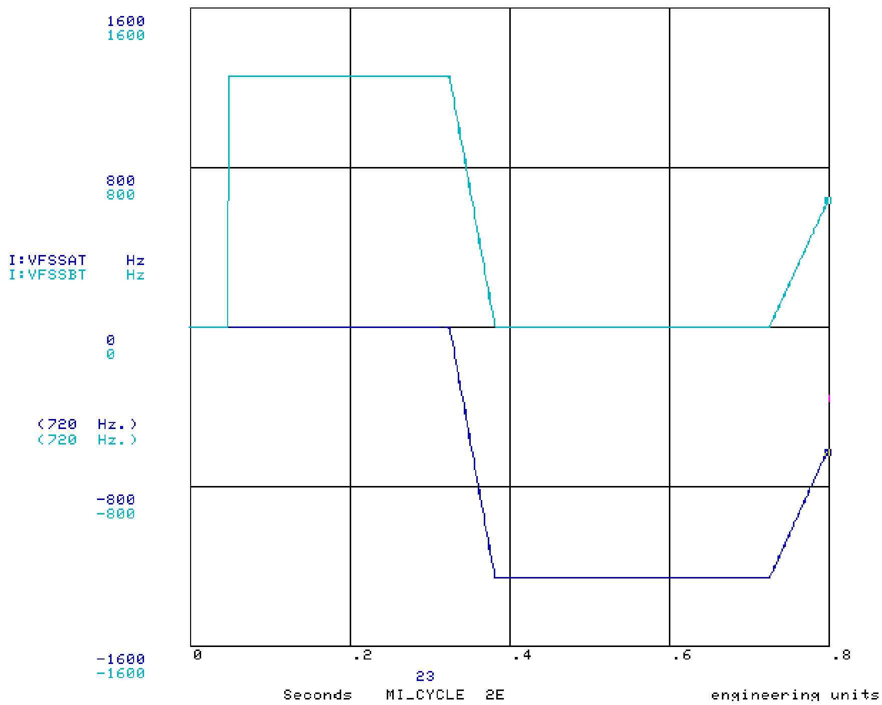


Figure 10: Study frequency curve for the 11-batch slip stacking of Proton Plan 1. Beam is injected on the central frequency (0 Hz) 11 times between 0.06 and 0.66 s. The frequencies of the two beams are adjusted (also changing the energy) until they slip fully and bracket the central frequency, at which time they are captured (0.8 s).

The Proton Plan 2 implementation of slip stacking in the Recycler will be entirely derived from the Main Injector experience with Run II and Proton Plan 1 [21]. The Recycler's circumference and gross lattice characteristics will be identical to the Main Injector's[9]. The RF used to keep the beam bunched while slipping is a moderate voltage of ~ 100 kV. As the Recycler will not be called upon to accelerate beam, it can have significantly fewer RF cavities, each designed with smaller R_s/Q. The reduction of shunt impedance and number of cavities will significantly improve the beam-loading situation. Additionally, a compensation system similar to the Main Injector's can be implemented.

[9] The Recycler presently has a modified lattice in the area where electron cooling takes place

The frequency scheme can also be optimized in the Recycler to reduce the number of acceleration/deceleration cycles and use less of the momentum aperture. A potential frequency schedule is shown in Figure 11. The first six batches are injected at a momentum corresponding to a frequency higher than the central by half the separation. The separation frequency is fixed, as in Proton Plan 1 to 1260 Hz. Those batches are then decelerated to an orbit below the central frequency by half the separation[10]. The other six batches are injected on the second RF. The beam can be extracted as a whole to the Main Injector without any further acceleration or deceleration.

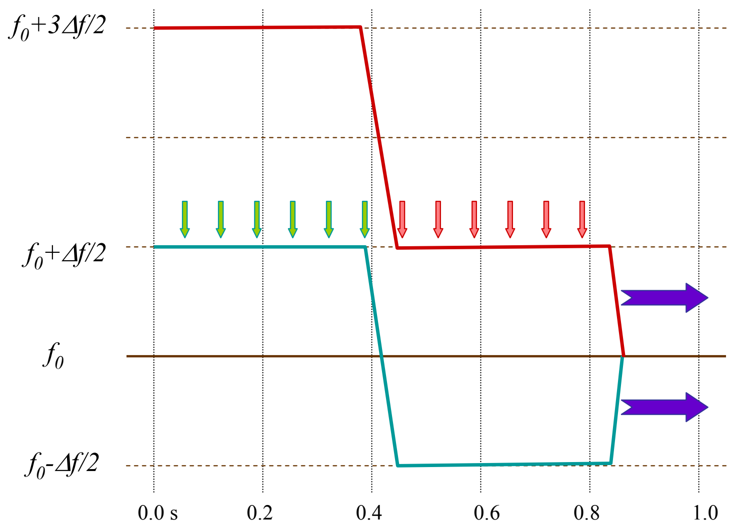


Figure 11: Proposed frequency scheme for Recycler slip stacking. Beam is injected six times above the central frequency by half the separation frequency. That beam is decelerated to below the central frequency to a slipping orbit and six more injections take place on the injection orbit. The beams are extracted in a single turn when they overlap in azimuth, one Booster tick after the last injection.

Slip stacking is expected to operate well in the Recycler for Proton Plan 2, but it cannot be tested until actually installed. The risks associated with slip stacking are that the loss levels will not be reduced sufficiently by the advances of Proton Plan 1, the move to the Recycler, and other Proton Plan 2 mitigation schemes. In such a case, the Recycler can still be used to increase the proton throughput of the complex. At the conclusion of Proton Plan 1, the Booster is expected to be able to deliver batches of 20-30% greater intensity than those useful for slip stacking[11]. These batches could be boxcar stacked in the Recycler[12], leading to 20-30% production gains. Additionally, the proposed scheme of batch compression using barrier buckets [22] might be possible in the Recycler as long

[10] Batches cannot be injected at different frequencies because the transfer line may not be able to handle the momentum difference, and because different frequencies are not compatible with the notch cogging system in the Booster.

[11] These larger batches from the Booster are possible by filling a larger longitudinal emittance than that useful for slip-stacking.

[12] The bunches in the Booster would require bunch rotation to fit inside the 300 kV buckets capable at this stage of the upgrades; the amount of rotation necessary would be less than that for slip stacking. If an additional two RF cavities are installed, so that 600 kV are available, then bunch rotation would not be needed at all.

as the LLRF system remains intact[13]. Batch compression has not been used operationally, as slip stacking has, but it has similar or greater potential for increasing proton throughputs. These two contingencies provide greater certainty that the Proton Plan 2 Recycler upgrades will improve proton throughput.

1.5.4 Booster

The Booster will be called upon to deliver 12 successive batches of 4.3×10^{12} protons every 1.33 s. The Proton Plan 1 goals include being able to deliver equivalent batches to the Main Injector for slip-stacking by 2009. Compared to Proton Plan 1, Proton Plan 2 will use 80% more protons from the Booster for the Main Injector; however, Proton Plan 1 will have an additional number of protons for the 8 GeV neutrino program which can be redirected to Proton Plan 2.

The critical factors in the Booster that are most likely to affect Proton Plan 2 are loss control and longitudinal emittance conservation. The Booster proton throughput is limited by proton losses; Proton Plan 1 is designed to reduce these losses, but the necessary proton rate for Proton Plan 2 has not yet been demonstrated. The momentum spread of the beam from the Booster is a primary factor in slip stacking efficiency. The momentum spread of ± 8 MeV/c (at 95%) is achieved by constraining the longitudinal emittance to no more than 0.08 eV·s and a bunch rotation. The Booster's transverse emittance is set by the injection and early capture process. A 95% normalized emittance of 15 π mm·mrad is typically achieved in each plane and adequate for operation.

The Booster nominally produces 8 GeV kinetic energy protons, bunched into 84 buckets (~82 extracted) of 53 MHz structure. The Booster cycles at a rate of 15 Hz; according to Proton Plan 1 only an average of 9 Hz is available for beam, but most of the upgrades for full 15 Hz repetition have been implemented.

While the devices in the Booster may be able to operate at 9 or 15 Hz, beam can only be accelerated if losses are sufficiently controlled. The Proton Plan 1 improvements are designed to decrease and control losses such that throughput can be improved. At the conclusion of Proton Plan 1 the Booster is estimated to provide 18.9×10^{16} protons/hour, with a fallback number of 13.0×10^{16}. Those estimates make assumptions about the users of the protons with regard to cogging which is estimated to incur 20% greater loss; adjusting to Proton Plan 2 uses the limits would be 17.2×10^{16} and 12.7×10^{16}. The anticipated Proton Plan 2 usage is 13×10^{16} protons/hour, which is slightly above the fallback and well below the design capability. The Proton Plan 2 proton consumption from the Booster will be achievable if Proton Plan 1 at least achieves its fallback goals.

To be useful for the slip-stacking, the Booster beam must be notched for extraction, have the notch cogged for extraction, the beam must be bunch rotated to reduce the momentum spread, and the beam must be phase locked to the Recycler 53 MHz RF. Additionally, longitudinal emittance must be kept suitably low and losses kept under established thresholds. All of these techniques are currently performed in the Booster; they each have their own liabilities, some of which are addressed by Proton Plan 1.

[13] Batch compression involves debunching, compression, and rebunching into 53 MHz. 300 kV is inadequate for a complete rebunching, so either time must be spent in the Main Injector for bunching, or two more RF cavities must be installed in the Recycler.

Notching removes the charge from 2-3 buckets of the bunched Booster beam at low energy, allowing for the rise time of the extraction kicker and thereby reducing the energy-weighted beam loss. Notching reduces the number of bunches from 84 to 81-82. The lost beam is substantially dumped into a set of collimators, but still contributes to activation. Proton Plan 1 will attempt to implement a notcher in the Linac, so that the buckets are vacant upon entry into the Booster. By removing the beam at a very low energy (maybe 20 keV) this loss source can be substantially reduced. Unfortunately, this technique is incompatible with cogging and could only be used on the first batch of each 12-batch cycle. A very fast kicker with rise time of < 8 ns could allow extraction without a notch (also obviating the need for cogging); such a system is under investigation in the Booster, but no design exists.

Cogging aligns the notch with the location for which the beam is intended in the Recycler. The alignment has nontrivial variation during the acceleration cycle, primarily resulting from small variations in the magnet currents between cycles. The cogging process involves creating the notch several ms into the Booster acceleration cycle and manipulating the beam horizontally throughout most of the remaining cycle. Creating the notch later produces greater losses due to the greater energy. The horizontal manipulations involve moving the beam centroid up to 3 mm through momentum deviation. Typically, no loss of beam is directly observed in conjunction with the manipulations. However, the beam motion reduces the available horizontal aperture available for tuning. No alternative method for cogging has been proposed and the system will likely only improve slightly due to more careful tuning. The amount of energy lost through notching and transverse motion required may be reduced if the regulation of the magnet power supplies is improved; this is currently under study within the Booster.

Bunch rotation reduces the momentum spread of the beam in the Booster at the expense of increasing bunch length. This rotation improves longitudinal matching to the slipping buckets in the Recycler. The slipping buckets are maintained with only ~ 100 kV/turn, so the energy width is very small, while the bunch length can be very large. Performing bunch rotation in the Booster was difficult due to beam loading and balancing problems associated with providing low gradients. More recently, the Booster has implemented bunch lengthening through the excitation of a quadrupole oscillation [23]; this method has been more successful at lengthening without distorting the bunch. The bunch rotation and longitudinal emittance must contrive to give a $\delta p \leq \pm 8$ MeV to fit within the slipping buckets. The nominal 95% longitudinal emittance to achieve this energy spread is 0.08 eV·s, but can be relaxed if the bunches can be lengthened more effectively.

Phase lock aligns the RF phase and frequency of the Booster beam to that of the Recycler, allowing bucket-to-bucket transfers into the slipping buckets. This system presently operates for transfers to the Main Injector and will operate identically for transfers to the Recycler. By fixing the frequency and phase, the beam's momentum and azimuth centroids are fixed and matched to the Recycler's. However, since the slip factors of the Booster and Recycler are different in value and sign, the Booster's maximum bending field must be controllable and consistent to ensure matching[14]. Such control is presently used in tuning the performance of slip stacking in the Main Injector.

1.5.5 Recycler

The Recycler is a permanent magnet 8 GeV storage ring with the same circumference as the Main Injector (7x that of the Booster), and similar gross lattice features of beta functions, tunes, dispersion, and momentum compaction. The Recycler is presently used to store and cool antiprotons for Run II. When suitably modified for Proton Plan 2, it will accept twelve batches of Booster beam, merge them into a length of six batches through slip stacking, and transfer them to the Main Injector in a single turn.

A significant obstacle to achieving slip stacking in the Main Injector was the beam loading induced on the main RF cavities while slipping the beam. Most of the RF cavities were required to have zero gradients, and the others used to slip the beam had only a fraction of their maximum gradient. The beam structure changes significantly during slipping, causing complicated DC and transient beam loading in the cavities. In order to prevent unacceptable distortion of the slipping buckets, a substantial beam-loading compensation scheme was implemented, including both feedforward and feedback loops [20].

The Recycler will use the same scheme as the Main Injector for slip stacking, so it will require similar control of beam loading distortion. The situation should be substantially simpler in the Recycler as it will only have two 53 MHz cavities, instead of the MI's 18 or 20. Additionally, the new cavities for the Recycler are being designed to have smaller R_s/Q by a factor of five. Nevertheless, a beam loading compensation system is expected to be necessary [17]; duplicating the features of the MI system will be adequate.

The transverse instability arising from the resistive wall effect is suppressed in the Main Injector through the use of negative chromaticity at injection and a bunch-by-bunch damping system [24]. The damping system is necessary to keep the chromaticity to reasonably small values. Instabilities are typically seeded by injection errors [25]. The Recycler beam pipe is smaller than the Main Injector's, leading to a larger resistive wall effect. Both pipes have a roughly elliptical cross section; in the horizontal, the Recycler's interior dimension is 20% smaller (96 mm vs. 120 mm); in the vertical it is 12 % smaller (44 mm vs. 50 mm). Considering that the smaller dimension (vertical) contributes more greatly and that substantial portions of each ring have non-standard beam pipes (different diameters), we conclude that the growth rate of coupled-bunch oscillations due to the resistive-wall transverse impedance should be no more than 50% greater in the Recycler than Main Injector. The transverse dampers in the Main Injector presently have a 500% gain margin; though at the Proton Plan 1 intensities this margin may be reduced[15]. A similarly designed system for the Recycler will accommodate the transverse instability.

---

[14] The Recycler, consisting predominantly of permanent magnets, cannot significantly change the momentum of its central orbit.

[15] From intensity scaling exercises the margin of 300% would be expected. The margin may ultimately be greater due to the longer bunch length of the beam injected for slip stacking. However, the details of how to damp injection oscillations in the Main Injector for Proton Plan have yet to be worked out. The immediate slipping of the beams complicates the procedure, potentially leading to a reduced damping efficiency. The possibility of using a narrow-band damping system for the dominant mode may alleviate the complication.

Explicit longitudinal damping is not performed in the Main Injector for slipping beam[16], and is assumed to not be necessary in Proton Plan 1. Damping is implicitly performed through beam loading compensation in the Main Injector, which will also be present in the Recycler.

No widespread formation of electron clouds is expected in the Recycler for Proton Plan 2. In the Main Injector only minimal and local electron activity has been observed for bunched beam. No electrons have been observed for slipping beam and no associated beam instabilities have been observed. The Recycler parameters will be substantially similar to the Main Injector. The electric field will be slightly higher at the beam pipe due to the smaller cross section, but the distance available for acceleration will also be smaller.

The space charge tune shifts experienced in the Recycler will be greater than those currently experienced for antiprotons. Experience in the Recycler have shown that coherent tune shifts are slightly smaller than a simple estimation [26] – this effect is likely due to the large portions of the ring which have larger beam pipes. Using those scalings, for Proton Plan 2 the coherent tune shifts will be ~ 0.06, which can be accommodated. The incoherent tune shifts will be comparable to those currently in the Recycler because, while the beam intensity will be 10× greater, the transverse emittance will also be ~ 8× larger. The maximum incoherent tune shift will be larger than that presently in the Recycler, to as much as 0.2; the Recycler regularly approaches these tune shifts during the period of mining when the azimuthal density is temporarily increased – the duration of the mining is longer than the time used to slip beam for Proton Plan 2.

The Recycler permanent magnets are made of strontium ferrite for, among other reasons, its radiation resistance. Tests of bulk demagnetization showed a loss of 0.03% with a dose of 100 MRad [27]. The Recycler design anticipates that field losses of up to ~ 1% can be corrected by realignment of the gradient magnets. Nevertheless, care must be taken to avoid widespread irradiation of the ferrites in excess of ~ 1 GRad. Such levels are unusual, and would only exist in localized, high-loss regions, and would likely not extend out to the full radius of the ferrites.

1.5.5.1 Beam Cleaning

We are proposing to an additional kicker in the Recycler that will ensure that the azimuthal gap used for injection is clear of beam prior to injection. The beam cleaning has the capacity to substantially reduce the uncontrolled loss that would otherwise heavily irradiate the injection region.

The process of slip stacking in the Main Injector is known to have an inefficiency of about 5% in ideal circumstances with high-intensity beam. However, the 5% of the beam is not immediately lost; instead it escapes from the slipping buckets and transits around the azimuth. The beam is then typically lost in two ways: further injections displace the escaped beam into a series of magnets, producing a local area of high irradiation; if not displaced, the beam will fail to be accelerated once the main ramp begins and be lost

[16] Longitudinal damping is performed for captured beam and other types of acceleration, leading to a reduction in longitudinal emittance. In Proton Plan 2 such beam conditions will still be limited to the Main Injector, not the Recycler.

longitudinally. Additionally, some portion is captured into the main RF's accelerating buckets; that portion of the beam is not typically lost, but does produce larger tails in the longitudinal distribution.

The losses from accelerating the beam will not occur inside the Recycler, only the large injection loss. From experience in the Main Injector, we can predict that the injection loss would be on the order of 1000 W for Proton Plan 2. Even spread over a larger area of up to 100 m with bumps (as is currently done in the Main Injector), the loss would lead to large radioactivation and potential component failure.

Instead of suffering the injection loss, we propose to include an additional kicker system, identical in kick to the injection kicker, but designed to extract circulating beam to the abort. This kicker would pulse immediately before injections (and the final extraction) to remove all beam from the injection and extraction gaps. Considering the rise and fall times involved, the beam cleaning system could reduce the injection losses by 95%.

1.5.6 Main Injector

The Main Injector will operate almost identically in Proton Plan 2 as in Proton Plan 1; the differences being that the slipping process will no longer occur in the MI, and that the ramp rate will be increased to reduce the cycle time. The improvements made in Proton Plan 1 will be necessary to run the Main Injector with reasonable losses.

Removal of the slipping process from the Main Injector to the Recycler reduces the low-voltage requirements on the MI RF system. Cavities will no longer need to provide zero gradient and will no longer have to deal with the detailed transients of slip stacking. Nevertheless, the cavities will sustain a large DC beam loading and still have the transient of the abort gap. The Proton Plan 1 beam-loading compensation will be adequate for these loadings.

A faster ramp rate is achieved in the Main Injector by adjusting the ramp rate and the fixed time portions of the ramp, as described later. The linear ramp rate is increased from 205 to 240 GeV/s; the magnet downramp (when no beam is present) is also quickened. Additionally, some time is trimmed from the flat top and bottom.

The faster ramp rate of 240 GeV/s is accommodated by adding two more RF stations to the existing 18. Calculations show that the maximum beam intensity and bucket area is more than adequate for Proton Plan 2 with these two new cavities [28]. The beam intensity does exceed the simple Robinson instability limit, but experience has shown that with beam-loading compensation the limit can be exceeded by a factor of 1.84. Additional studies suggest that the limit may be exceeded up to a factor of 2.5.

A set of collimators will be installed in the Main Injector for Proton Plan 1 to intercept the beam that fails to accelerate, and to provide a limiting aperture [29]. These collimators are necessary for Proton Plan 2 to intercept the same type of loss. The two-stage system may have to be reconfigured for Proton Plan 2, but the system is flexible enough such that relocation of secondary collimators will not have a negative effect on its efficiency.

The Main Injector does not presently exhibit any regular transition loss with slip-stacked beam. Occasionally, a loss as large as 0.2% is observed, but can be reduced with careful tuning. We adopt 0.2% as an upper bound for regular Proton Plan 2 operation.

1.5.7 Loss Distribution and Management

Without care, the performance of Proton Plan 2 upgrades may be limited by losses in the Main Injector tunnel. As the Recycler and Main Injector share the same tunnel, their loss budgets must be combined. For estimating future loss distributions we have the current "2+5" operation which has some similarities to Proton Plan 2 beam cycle. Eventually, Proton Plan 1 will commission 11-batch operation; the 11-batches will be injected using slip-stacking in a much more similar way to Proton Plan 2 operation and provide a better basis for estimate.

The beam loss associated with slip stacking has three principal modes, all occurring at 8-10 GeV. The first is beam that has leaked into the injection gap portion of the azimuth and is displaced by later injections; the second is beam lost slowly during the extended period at 8 GeV as a lifetime; the third is beam not contained in the main RF buckets and lost as the magnets start to ramp. Some of the loss is fungible between the categories; for instance, by antidumping buckets which should be empty some portion of the injection and ramp losses can be converted to lifetime losses.

To establish a loss baseline, we consider the standard "2+5" operation cycle that is presently used for antiproton and neutrino production. In this case two high-intensity batches of Booster beam are slipped into one; five more injections of beam then occur which are not slip stacked. An example of the 2+5 cycle is shown in Figure 12 along with a "6 batch" cycle, where six successive injections occur without slip stacking.

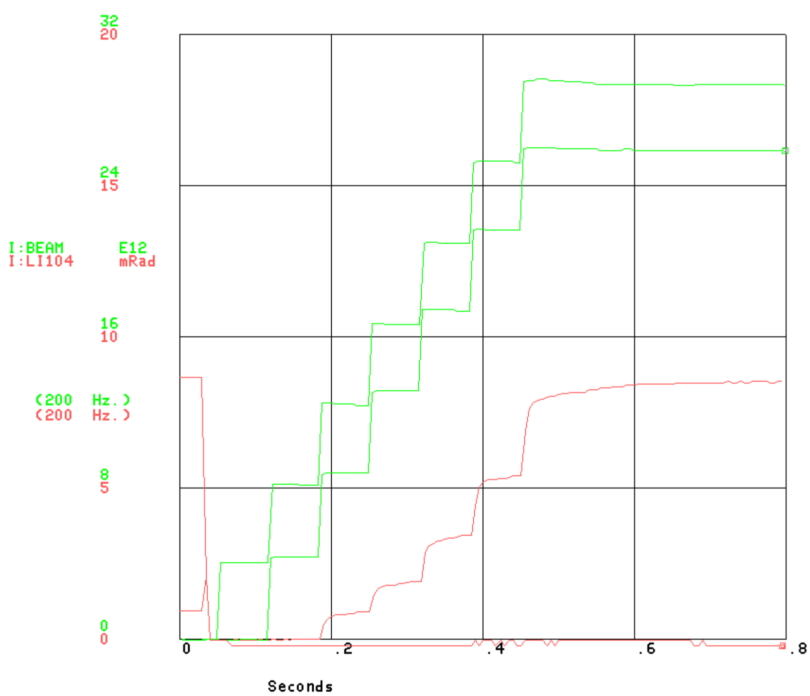


Figure 12: Beam current and injection loss for two examples of well-tuned beam. The higher is the typical "2+5" beam, the lower is the "6 batch" which does not use slip stacking, and thus has smaller

losses. Loss in this plot is indicated by a negative slope in the charge for the lifetime and ramp losses, or for injection loss as a rapid increase in the signal measured at the loss monitor just downstream of the injection location.

The injection losses in Figure 12 are indicated by the increase of the red trace, which is the integrated loss measured at a loss monitor downstream of the injection kicker and Lambertson. The amount of injection loss is primarily measured as the difference between the amount of beam injected (as measured by a transfer line toroid) and the current increase in the MI. There is some correspondence between the loss quantity and the loss monitor signal, but the correlation is not consistent. The losses on the second injection are minimal as it is spaced widely from the first and the uncaptured beam has not yet had much time to slip around the ring. The losses occur on each of the later injections when the injection kick displaces the circulating, uncaptured beam[17]. In comparison, the six batch cycle suffers no measurable injection loss. The injection loss is spread across about 100 m of the ring[18] producing several hot spots which can be greater than 2 R/hr. when measured on contact with the beampipe.

The “lifetime” losses appear as a slope in the measured beam charge. The beam does develop a legitimate lifetime with high-intensity bunches such that beam leaks out in a continuous manner; this loss can also be observed on the 6 batch cycles. An additional effect is that buckets which are supposed to be empty are pinged with the bunch-by-bunch dampers to remove beam that might have leaked there. The rationale is to convert a portion of the injection and ramp losses into a more distributed loss around the ring or into collimators.

The ramp loss occurs 50-150 ms after the last injection and is also indicated by a slope in the charge. This loss is from large amplitude beam that shares azimuth with the nominal beam, but is not contained within the RF buckets. As the magnets ramp and the nominal beam is accelerated, the large amplitude beam will spiral into the machine and be lost.

[17] The losses increase on each of the later injections as the uncaptured beam moves in preferentially one direction around the ring, such that the later injections displace a greater quantity.

[18] The loss was intentionally spread over a larger area by displacing the centroid of the beam through next few cells.

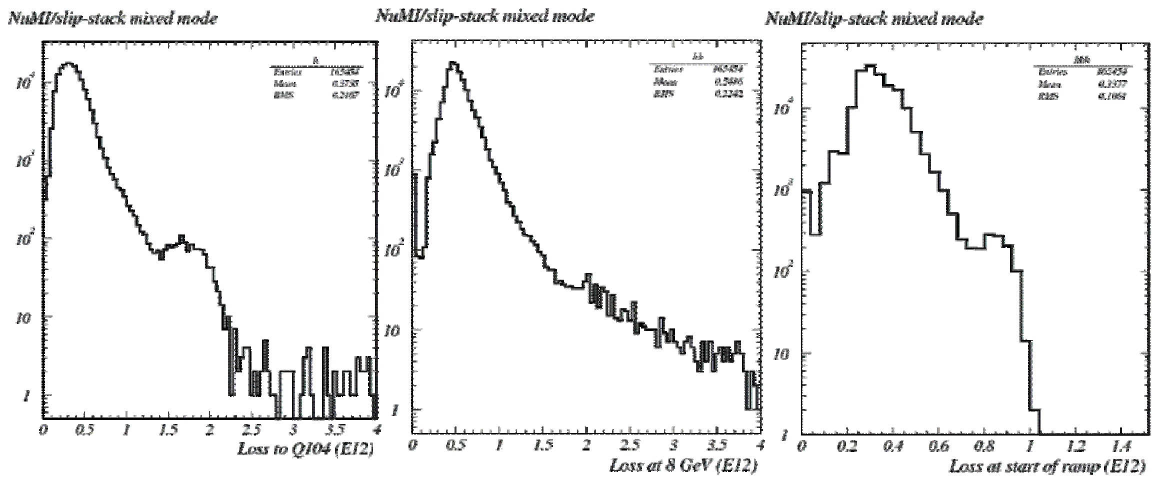


Figure 13: Histograms of loss types measured over several days of operation with "2+5" operation. From left to right, the losses are those measured at injection, due to lifetime, and on the ramp. This data was taken while pinging out "empty" buckets; without the pinging about 40% of the 8 GeV lifetime losses occur at injection instead.

The three types of losses were monitored for a period of about one week of regular 2+5 operation, and histogrammed in Figure 13. The total loss is of the order of 4% and the Proton Plan 1 goal is to achieve 5% loss with 11 batch operation. When accounting for the affect of pinging, the losses are distributed as 45% in the injection gaps, 30% due to lifetime, and 25% on the ramp.

The loss distribution will change with 11 batch operation, though the pattern is not yet established. Injection losses may be greater due to the greater number of injections; however, the later injected batches that are slipped will have a smaller proportion of their beam kicked out. The true lifetime loss may be greater due to the increased time at 8 GeV; the pinged out beam will likely be decreased because a greater portion of the azimuth is filled with beam. The ramp loss as a proportion of slip-stacked beam will be similar, but may be modified due to changes in the other two losses. For the present, we take the 2+5 loss distribution as a baseline with the intent that it be modified when 11 batch operation is established[19].

We classify the character of beam loss generally as "controlled" or "uncontrolled". Controlled losses are those that occur in specific locations where large collections of materials (such as collimators or beam dumps) absorb a large portion of the deposited energy and contain the resulting radioactivation within them. Uncontrolled losses occur elsewhere in the ring, the deposited energy going into the beampipe, magnets, other components, or the tunnel itself.

The major component of loss management will be directing inevitable beam loss such that it is controlled. Beyond minimizing the quantity of losses, the two methods for controlling losses are collimation and "beam cleaning".

---

[19] 11 batch studies have been underway for over a year. However, continued modification to the LLRF and BLC systems has been necessary to make progress toward operation. As of writing, the measured loss distributions are not directly useful for Proton Plan 2 loss predictions.

Collimation, as mentioned in the Main Injector section, will be accomplished with a two-stage collimation system installed for Proton Plan 1. This system is primarily designed to intercept the beam that fails to accelerate and spirals in. A primary scatterer will intercept the low momentum beam and a series of large secondary collimators will capture the bulk of the lost beam and shower. Additionally, the collimator should be able to provide a limiting aperture, such that large amplitude ring losses will also be contained. The system is designed to contain 90% of such losses to a local region. This set of collimators will be used in Proton Plan 2 to intercept the ramp loss, but will be of minimal use for collecting the lifetime loss as that will occur predominantly in the Recycler.

Beam cleaning is described above in the Recycler section. It will remove the injection loss to the MI/RR beam abort. Its kick will completely remove beam in the injection gap; however, there will be some uncontrolled loss at the rise and fall of the field[20]. The efficiency is thus about 95%, and will depend on the precise magnet waveform achieved.

Specific limits have not yet been established for in-tunnel radiation. Proton Plan 1 intends to eventually set individual limits at every loss monitor location once the losses are correlated to residual radiation. Such limits will be soft: they are designed to guide tuning and are not hard limits on radioactivation. A rule of thumb is that uncontrolled losses must be maintained below 1 W/m for hand-on maintenance. However, the circumference of the Main Injector is so great that local hot spots could still develop if the rule of thumb is achieved. Present losses are known to be spread unevenly around the Main Injector; see [30] for a survey of radiation levels in the Main Injector, and see [31] for an analysis of loss monitoring. Therefore, the Proton Plan 2 goal for distributed losses must be less than 1 W/m.

The above numbers are used to calculate the loss levels quoted in the introduction's parameter table (Table 3). For a 5% loss, Proton Plan 2 will deposit 1060 W in the abort, 560 W in the MI collimators, and have 1110 W of uncontrolled losses. Distributed about the ring the uncontrolled losses would be 0.34 W/m.

1.5.8 References

14. The Proton Plan 1 Design Handbook is found on its webpage: http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.shtml. A public site viewable outside Fermilab is: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml

15. B. Boussard and Y. Mizumachi, "Production of Beams with High Line-Density by Azimuthal Combination of Bunches in a Synchrotron", IEEE Trans. Nucl. Sci., NS-26. No.3, June 1979, pp. 3623-5.

16. The Run II project homepage is http://www-ad.fnal.gov/run2upgrade/. Slip stacking was an addition to the original Run II designs.

17. K. Seiya *et al.*, "Status of Slip Stacking at Fermilab Main Injector" PAC 2005, MOPA004; FERMILAB-CONF-05-110-AD.

18. F. E. Mills, BNL Internal Report AADD 176, 1971.

---

[20] The loss dues to the rise and fall times will be of injection gap beam that would otherwise be displaced during injection. However, it will be deposited in the extraction area magnets and beampipe, and is thus considered uncontrolled.

19. S. Shukla *et al.*, “Slip Stacking in the Fermilab Main Injector”, 1996 DPF / DPB Summer Study on New Directions for High-Energy Physics, eConf C960625:Acc015, 1996.

20. J. Dey and I. Kourbanis, “53 MHz Beam Loading Compensation for Slip Stacking in the Fermilab Main Injector”, PAC 2005, TPPT027, FERMILAB-CONF-05-175-AD.

21. K. Seiya and I. Kourbanis, “Slip Stacking in MI”, FNAL-Beams-doc-2179, 2006.

22. G. W. Foster *et al.* “Beam Manipulation and Compression Using Broadband RF Systems in the Fermilab Main Injector and Recycler” EPAC 2004, TUPLT149, p. 1479.

23. M. Bai *et al.* “Adiabatic Excitation of Longitudinal Bunch Shape Oscillations” PRST-AB 3, p. 064001 (2000).

24. P. Adamson et al., “Operational Performance of a Bunch by Bunch Digital Damper in the Fermilab Main Injector”, PAC 2005, MPPP015, FERMILAB-CONF-05-145-AD.

25. V. Balbekov, “Recycler Transverse Instability in Context of Proton Plan (Rigid Modes Instability at Dominating Space Charge)”, internal Recycler note, 2006.

26. A. Shemyakin, “Tune Shifts in the Recycler”, FNAL-Beams-doc-2530, 2006.

27. M. Hu, “The Fermilab Recycler Ring”, PAC 2001, MOPA006; FERMILAB-CONF-01-187-E.

28. I. Kourbanis, “Beam Acceleration Capabilities of the Present MI RF System”, FNAL-Beams-doc-1927, 2006.

29. B. Brown *et al.*, “Beam collimation in the Main Injector at Slip-Stacking Injection”, FNAL-Beams-doc-2330, 2006.

30. B. Brown, “Residual Radiation Hints for Aperture and Alignment Issues in the Main Injector”, FNAL-Beams-doc-1382, 2005.

31. D. Cherdack., “MI Loss Monitor Review”, FNAL-Beams-doc-2538, 2006.

2 Elements of the Plan

2.1 Booster Upgrades (WBS 1.1)

2.1.1 Introduction

Proton Plan 2 intrinsically relies on the success of Proton Plan 1, which is the current campaign to deliver protons to both NuMI and the 8 GeV neutrino program. Some details of Proton Plan 1 are found in Section 1.1, but as far as the Booster is concerned, its primary goals are:

- Increasing Booster efficiency to reduce uncontrolled beam loss.
- Achieving acceptable beam quality for slip stacking in the Main Injector.
- Increasing the maximum average repetition rate of the Booster to at least 9Hz, including required beam free conditioning pulses.

The first two goals, if achieved, are also adequate for Proton Plan 2. However, because they are so important, there are milestones in the Proton Plan 2 plan to evaluate the success of these efforts. These would also provide natural places to add scope to Proton Plan 2 in the event that Proton Plan 1 falls short of expectations. The repetition rate remains an issue, and is discussed below.

2.1.2 Booster Repetition Rates

Proton Plan 1 requires the Booster to operate at an average repetition rate of about 9Hz. This was well above the capabilities of the system when the neutrino program began.

The general philosophy of the Plan was to understand all the rate limitations of the system and if significant improvements were needed to operate at 9Hz, to make those improvements robust to the full 15 Hz rate of the machine.

At the time of this writing, the magnetic components of the Booster are believe to all be capable of continuous 15 Hz operation and the only rate limitations come from the RF system, which presently limits the average repetition rate to somewhere between 9 and 10 Hz.

The Proton Plan 2 program requires the Booster to operate at just over 10 Hz to supply NuMI alone, with higher rate required if we wish to continue operation of the 8 GeV program.

The SNuMI program requires the Booster to run at 15 Hz continuously. For that reason, we will continue the policy of making any significant improvements required for Proton Plan 2 adequate for the full 15 Hz SNuMI operation, budget permitting.

2.1.2.1 Cavity Tuner Cooling Study/Modifications

It is possible that the three loaded tuning cores on the Booster RF cavities may overheat at high repetition rate. In particular the “cores”, which form part of the matching section are believed to be vulnerable to this.

This will be tested in a series of measurements at high repetition rate. If it’s found to be a problem, then these cores will need to be water cooled. There are cooling channels provided for this, but many of them leak and will need to be reworked. The exact scope of this effort, if required, is still being determined.

2.1.2.2 Anode Power Supply Replacement

The Booster RF system requires two large power supplies which supply voltage and current to the anodes of the power amplifier tubes. These produce 30 kV at roughly 50 A. The supplies are original to the laboratory and their reliability at high repetition rate is a concern. It is planned to study the existing supplies to determine whether they will be reliable at high repetition rate, or if some sort of refurbishment can make them reliable. If, on the other hand, they need to be replaced entirely, this will be a major project which will probably be postponed until the SNuMI project.

2.1.2.3 Bias Supply Transformers

The Booster has large power supplies to supply the bias current to the ferrite loaded tuners that control the resonant frequency of the RF cavities during acceleration. There is one such supply for each cavity, and they are divided into two types. One type is capable of pulsing continuously at 15Hz, while the other type is limited to roughly 10 Hz by the overheating of a transformer in the power supply.

In order to go to 15 Hz, that transformer will have to be replaced with a more robust version, which also requires some associated redesign work in the cabinet.

2.1.2.4 Feeder

There is some concern that the 15 Hz repetition rate might put an unacceptable load on the 13.8 kV feeder which carries power from the substation to the Booster. Preliminary studies indicate that the load is probably acceptable, but we are leaving this item as a place holder until a final determination is made.

2.1.2.5 480 V Distribution System

Some of the 480 V distribution lines to the RF system share conduits which requires de-rating of their capacity. Whether this issue will limit the total average repetition rate to something less than 15 Hz is currently being investigated with the help of an outside consultant.

2.1.3 Beam Quality

Efficient slip stacking of beam in the Main Injector places requirements on the stability and quality of the beam out of the Booster. In principle, the beam quality required for Proton Plan 1 should be sufficient for the needs of Proton Plan 2. However, experience has shown that this particular area may require vigilance, so this item is currently included as a place holder.

2.2 Recycler Ring Upgrades (WBS 1.2)

The Recycler currently serves as the main anti-proton storage ring for the Tevatron Collider program. Through the use of stochastic and electron cooling, greater than 4e12 anti-protons have been stored, with lifetime greater than 500 hours. The transverse acceptance is ~65 π mm mr (95% normalized emittance) and the momentum acceptance is ~1.5%. As the Recycler is the same size as the Main Injector, it is possible to do a single turn fill (~11 μsec), minimizing the proton injection time in the cycle and maximizing the protons on target.

The current R22 line (for pbar injection or proton extraction from the Recycler) and R32 line (for pbar extraction or proton injection into the Recycler) will not be adequate in the Proton Plan 2 era. The original R22 line was designed for 10π pbar beams, not 15π proton beams we anticipate from the Booster, with a large counterwave in both the MI and the Recycler necessary. The R32 line allows for proton injection through the MI, while we want direct injection from the Booster. These lines will be decommissioned.

To convert from an anti-proton storage ring to a proton pre-injector, filling the Main Injector every 1.3 seconds, it will be necessary to remove anti-proton specific devices in the Recycler, build new injection and extraction lines, build new abort kickers, build a new 53 MHz RF system, and upgrade the instrumentation. In sections below, we will present the project components in detail. We anticipate that all of the conversion activities will take place during a single shutdown period after the Tevatron Collider program ends.

2.2.1 Decommission Pbar Devices in the Tunnel

As the Recycler will no longer circulate anti-protons, we believe it best to remove anti-proton specific devices from the ring. These fall into two categories: (1) anti-proton cooling devices and (2) anti-proton transfer line devices.

2.2.1.1 Removal of Stochastic Cooling Tanks

The Recycler stochastic cooling system consists of pickup tanks in the RR 21 sector and the kicker tanks in the RR 10 sector. The tanks and all the support electronics will be removed from the tunnel and replaced with beam pipe (in the 21 sector) or the injection area devices (in the 10 sector). The removal is a well-understood task which is anticipated to take 8 technicians 4 weeks to complete. It should be one of the first tasks done during the conversion shutdown period.

2.2.1.2 Removal of ECool

The Recycler electron cooling system consists of a 6 MV Pelletron in the MI 31 service building, 4.3 MeV electron transfer lines, a 20 m cooling section populated by solenoids, and lattice matching sections for the cooling section. We wish to preserve the system for possible future use (at Fermilab or elsewhere).

In this task, we will remove and package the solenoids for future use, remove the sections of the transfer lines in the MI tunnel enclosure, and remove all 38 Recycler permanent magnets between 301 and 309 (the cooling insert). These magnets will be sent to Technical Division to be refurbished and used again in the rebuilt MI 30 straight section (see Section 2.2.4, “Design and Construction of Injection and Extraction Kickers”) and the transfer lines (see Sections 2.2.2, “New Injection Line” and 2.2.3, “New Extraction Line”).

As the cooling section solenoids and electron transfer lines were installed in a recent shutdown (summer 2004), the removal is also a well-understood task. As the magnets will need to be refurbished and installed in other areas of the Recycler during the conversion shutdown, this task should be one of the first ones scheduled.

2.2.1.3 R22 Line Removal

The R22 line is the anti-proton injection line from the Main Injector to the Recycler. We plan on removing the Lambertson magnets in the Main Injector (at MI Q222) and the Recycler (at Q214) and rebuilding the vacuum sections in both machines. We also anticipate removing instrumentation from the line for use in the new transfer lines. In the conversion shutdown, we do not plan on removing all the components and stands. As the instrumentation will be utilized again, this task should also be done early in the shutdown.

2.2.1.4 R32 Line Removal

The R32 line is the anti-proton extraction line from the Recycler to the Main Injector. We plan on removing the Lambertson magnets in the Main Injector (at MI Q321) and the Recycler (at Q328) and rebuilding the vacuum sections in both machines. We also anticipate removing instrumentation from the line for use in the new transfer lines. In the conversion shutdown, we do not plan on removing all the components and stands. As the instrumentation will be utilized again, this task should also be done early in the shutdown.

2.2.2 New Injection Line

We are designing a new injection line to take protons directly from the MI 8 line into the Recycler. The MI 8 line transfers 8 GeV protons from the Booster to the Main Injector tunnel, where a horizontal switching magnet directs them into the Main Injector or the MiniBoone target. We want to preserve the ability to inject into the Main Injector and transfer beam to the MiniBoone target, so we plan on installing a vertical switching magnet (upstream of the horizontal switching magnet) to direct protons into the Recycler.

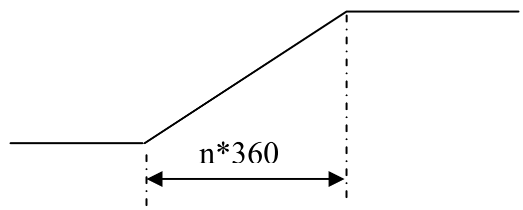
The schedule driver for this task is the injection kicker design. The specifications on the kicker include both a fast rise (38 nsec) time and fast fall (38 nsec) time so as not to disturb other protons circulating in the machine. We also anticipate a horizontal kick. These are very stringent requirements on the kicker. We plan on building a prototype magnet during FY07, with further construction to follow.

2.2.2.1 General thoughts of the design

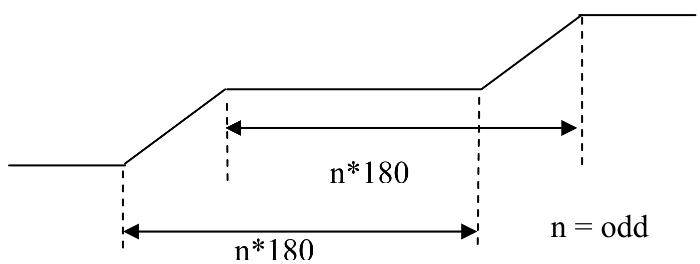
Two generic features to consider in the MI/RR transfer lines:

1. the geometry of the vertical bends
2. the plane of the injection/extraction and transfer layout

The vertical separation between the MI and RR is 56”. Particular attention must be placed on making the transfer line vertically achromatic as not to introduce a vertical dispersion mismatch. Note that the dispersion may only be created or canceled by dipole fields and the phase of the dispersion propagates as the betatron phase. There are two generic features to be considered as shown in Figure 14.



a. only two bend centers needed but they must be 360^{o} apart



b. four bend centers, requires 180^{o} between two same sign bends

Figure 14: Two generic features for vertical bending.

In Figure 14 a, vertical dipoles are separated by 2π in phase advance, In a 90^{o} FODO lattice like the MI and Recycler, this requires the vertical dipoles be placed in each ring with an offset of 8 half-cells if the transfer line keeps the lattice of the rings (i.e. 90^{o} phase advance). If the kickers are included, then the kickers are separated by 10 half-cells. In Figure 14 b, the two up bends must be n*π and independently, the two down bends must be n*π apart. This configuration naturally lends itself to keeping the transfer line FODO structure the same as the MI/Recycler and eases matching constraints. This is the procedure used for the existing MI<-> Recycler transfers. We will take this procedure for the new transfer lines.

2.2.2.2 Specific Design Details

For beam from booster to Recycler, we would like to follow the trajectory of existing MI-8 line to Main Injector, but use a switch magnet to bend the beam up while keeping the existing transfer injection line to MI in use. We found a simple and a clean solution as shown in red in Figure 15. A switching magnet (VUP1) can be placed between Q848 (SQA) and PDDR1 (8DH), where a 4.5m long drift space is available. At an elevation of about 28", a dipole magnet (VDN1) bends the beam down, and the beam line follows the existing transfer line on a flat level. After Q852, another dipole magnet (VUP2) raises the beam up again, and a dipole magnet (VDN2) provides the beam another bend down. All four vertical bends are the same strength such that the vertical dispersion may be canceled by placing the VUP1 and VUP2 (the up bends) 180^{o} apart and VDN1 and VD2 (the down bends) 180^{o} apart. VDN2 and all the dipole magnets for horizontal bending are with slight rolls due to vertical incline. A Lambertson magnet (RRLAM) with vertical bending angle is placed before quads 102 in the Recycler ring, and a horizontal kicker at 104, 90^{o} phase difference downstream of RRLAM. The beam is being injected vertically by the Lambertson magnet, which means that the injected beam is on the vertical closed orbit and offset horizontally from the closed orbit. This horizontal offset translates into a pure angular error 90^{o} downstream (at Q104), which can then be removed via the horizontal kickers. The injected beam has been offset 25 mm (outside of the Recycler ring) with respect to the Recycler beamline center. A 3-bump using the correctors at 100, 102, and 104 puts the circulating beam orbit at 21 mm (inside of the Recycler ring) through the Lambertson magnet. The kicker strength required is a bit more than ~300 G-m total. One concern here is that the horizontal kicker needs to have a fast rise/fall time (~40ns).

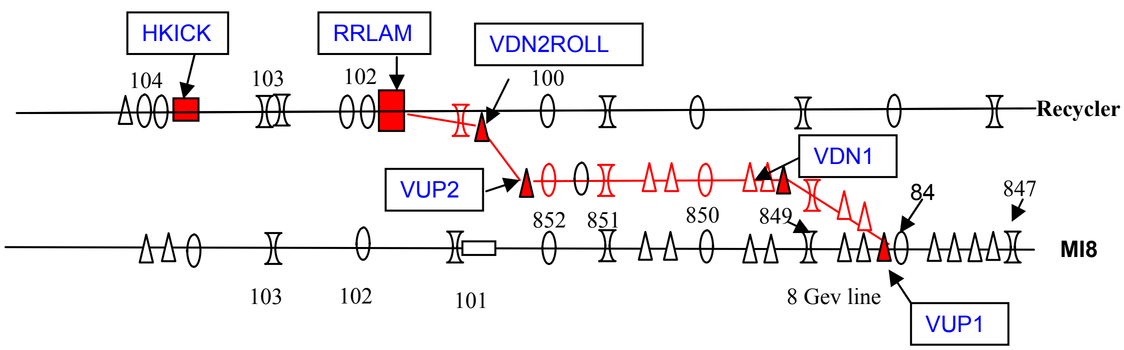


Figure 15: Cartoon of MI-8 to the Recycler transfer line

The equivalent focusing quadrupole magnets for matching the beam line lattice function will be replaced by a group of permanent magnets, which are available from the existing Recycler transfer lines, seen in Figure 16. Each group consists of two focusing or defocusing permanent quadrupole magnets, with two powered trim quads in the center providing ±20% tuning ability. Horizontal or vertical dipole correctors and BPMs are placed at the entrance and exit of the group respectively, according to the focusing or defocusing quads. There will be a loss monitor and a multi-wire installed for each group for beam loss and profile measurement. The multi-wire should be good for high intensity beam (stage 2) (just as the newly installed multi-wire devices in the MI-8 line).

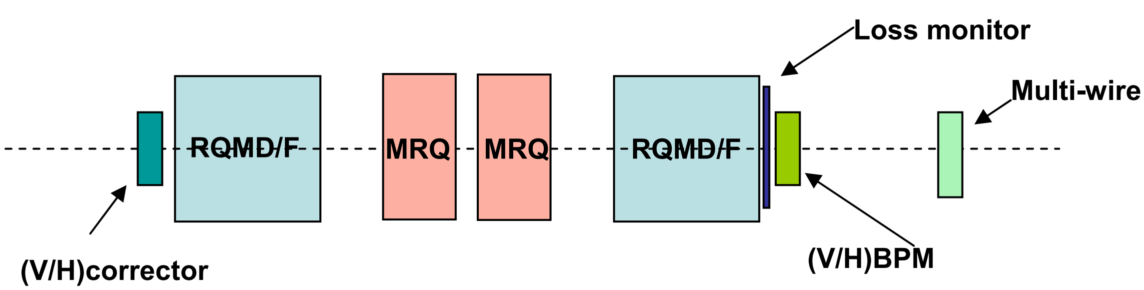


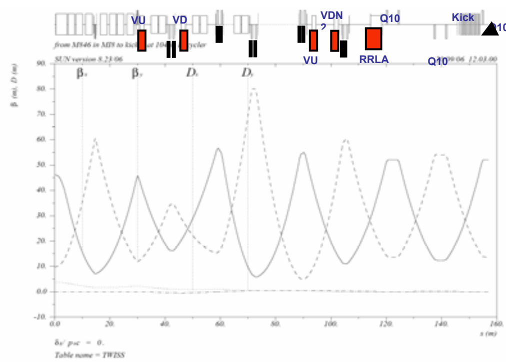
Figure 16: Permanent quadrupole magnets plus two trim quads

Figure 17a and Figure 17b give lattice function output from MAD and the corresponding beam size respectively. The beam size is calculated as follows:

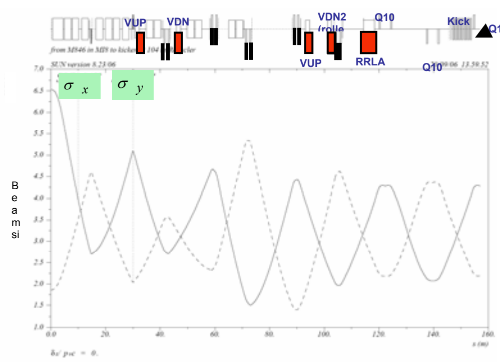
$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y} \cdot \varepsilon_{x,y}}{(\beta\gamma)\cdot 6\pi} + D_{x,y}{}^2 \delta^2}$$

Here (βγ)=0.994475*9.526019=9.47339, Emittance: $\varepsilon x=\varepsilon y=20\pi$ mm-mrad, Maximum momentum deviation: $\delta=\Delta p/p=1.4\times10-3$(in case of stage 2).

Table 5 and Table 6 list the requirements for the magnets to be used for the injection line.



(a)



(b)

Figure 17: Injection line output from MAD: (a) lattice functions (b) beam size

Magnets to be Used	Type	Length (m)	Number required	θ (mrad)	Tilt[1] (rad)	B_o (kG)	B_1 (kG/m)	Current (Amp)
VUP1[2]	ADCW	1.524	1	47.2	-π/2	9.183	-	984
PDD[3]	?	2.4638	1	19.208351	0	5.695	-	-
PDDR1	?	2.4638	1	19.208351	-0.00046875	5.695	-	-
PDDR2	PDD	2.4638	1	19.208351	-0.00135417	5.695	-	-
PDDX1 PDDX2 PDDX3 PDDX4	PDD	2.4638	4	19.208351	-0.001805	5.695	-	-
VDN1[4]	ADCW	1.524	1	47.2	π/2	9.183	-	984
VUP2[4]	ADCW	1.524	1	47.2	-π/2	9.183	-	984
VDN2[4]	ADCW	1.524	1	47.2	0.602450133	9.183	-	984
QR8492[5] QR8493 QR8502 QR8503 QR8512 QR8513 QR8522 QR8523 QR8532 QR8533	MQTM	0.3048	10	-	-	-	2.7	10
QR8491 QR8494	RQMD	0.508	2	-	-	-	-23.1730	-
QR8501 QR8504	RQMF	0.508	2	-	-	-	28.8098	-
QR8511 QR8514	RQMD	0.508	2	-	-	-	-30.5903	-
QR8521 QR8524	RQMF	0.508	2	-	-	-	29.1850	
QR8491 QR8494	RQMD	0.508	2	-	-	-	-30.0379	-

Table 5: lists the requirements for the magnets to be used for the injection line.

1) A tilt angle of π/2 implies a vertical bend.

2) VUP1 is a switching magnet, it needs to be ramped, and the ramp rate is 15Hz

3) PDD is the dipole magnet for horizontal bending, just after Q848 in MI-8 line, it needs to be replaced by a mirror magnet, respect to the PDDR1, the dipole magnet for horizontal bending in the injection beam line just after the switching magnets.

4) VDN1, VUP2, VDN2 are all ramp magnets, the ramp time is every 1.33 second (MI cycle time). It needs to hold (1/15)*12=0.8 second at flat-top for 12 batches of the beam to go through.

5) The transfer function for the powered trim quads in 0.27 kG-m/m/Amp which means for 10 Amps you get 2.7 kG which is about a 10 % correction.

Magnets to be Used	Type	Length (m)	Number required	θ (mrad)	Tilt (rad)	B_o (kG)	B_1 (kG/m)	Current (Amp)
RRLAM	RR-214	4.064	1	23	π/2	1.687	-	
RRKICK	K104	0.4	9	0.145024	0	0.043	-	500
VTR49 VTR51 VTR53	VDC		3					5
VHR50 VHR52	HDC		2					5

Table 6: Requirement of the magnets to be used for the injection line.(continued…)

For injection line, we found from Figure 17b that the maximum beam size in the horizontal plane is σ_x=4.95mm, σ_y=2.08 at the entrance of VUP1, the switching magnet. We plan on using an ADCW, which is a modified ADC magnet with a larger gap (from a 1.5" to a 2.12"). The maximum beam size in the vertical plane σ_x=1.59mm, σ_y=5.34mm at QR8511, a trim quad location. For the quads to be used in both transfer lines, the physical aperture is 3" (76.2mm) round, that means we have more than 16* σ_x, and14* σ_y available physical aperture in both planes at all the quadrupole magnets. With the modified ADCW, the horizontal aperture is acceptable (see Table 7). The apertures in the vertical plane are also acceptable.

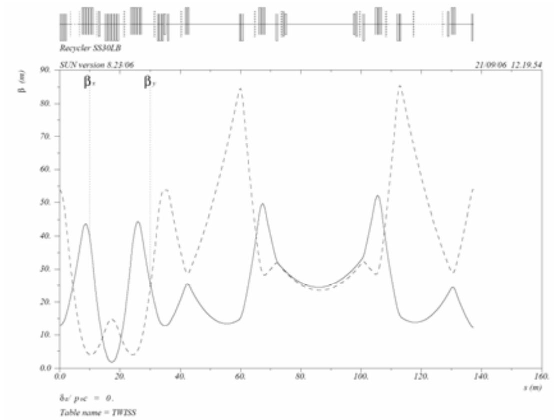
Locations		β_x (m)	β_y (m)	D_x (m)	D_y (m)	σ_x (mm)	σ_y (mm)	Available aperture	
								x (σ_x)	y (σ_y)
Injection line	VUP1	38.413	14.030	1.973	-0.036	4.95	2.08	**10.3**	38.4
	VDN1	23.104	26.204	0.868	-0.514	3.10	3.12	16.4	27.8
	VUP2	36.907	11.980	0.236	0.414	3.62	2.13	14.0	39
	VDN2	13.745	47.984	0	0.271	2.20	4.13	23.1	20
Extraction line	VUP1	51.813	13.129	0	0.405	4.11	2.45	12.4	32.9
	VDN2	52.540	13.825	0	-0.202	3.93	2.27	12.9	33.9

Table 7: Available apertures at ADCW magnets

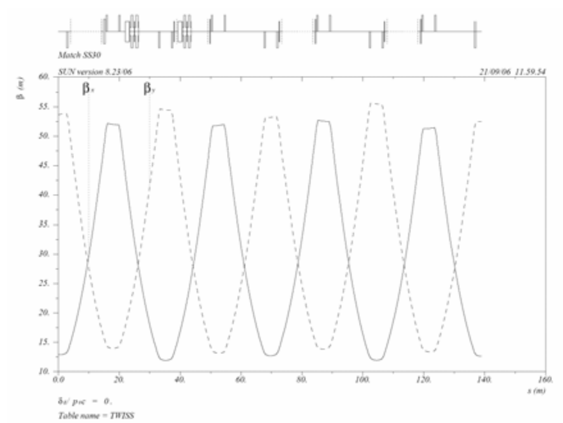
2.2.3 New Extraction Line

We are designing a new extraction line to take protons from the Recycler to the Main Injector, making use of the MI 30 straight section. The MI-30 straight section is a "D-D 8 half-cell" straight section, which starts at 301 and ends at 309--both horizontally defocusing locations. The MI lattice is a periodic FODO in the region. The Recycler lattice contains the symmetric electron-cooling insert between 305 and 307; the remainder of that Recycler straight section is roughly a FODO section, but is not periodic. The Recycler straight section between Q301 and 309 could be replaced with the FODO lattice, as in the initial Recycler design. Figure 18a and Figure 18b give the beta functions of the two types of the lattice.

Using the method in Figure 14 b, the beam line would start with an extraction kicker at 232 in the Recycler, and bend the beam down with a Recycler style Lambertson magnet located at 302. The replacement with a FODO lattice is also required to make room for putting a Lambertson magnet at 302--although it has no impact on the beam line. The beamline will follow the same lattice structure of the Recycler ring; that means it will be also a "D-D 8 half cell". There would be an up bend at 304 and the second down bean at 306(180^o phase). The MI Lambertson (MI style ILA) magnet would be located at 308, 180^o downstream of 304, which would put the beam on the MI vertical closed orbit. Ideally, the MI injection kicker would be located 90^o downstream of the Lambertson at 310, however the MI dipoles between 309 and 310 preclude such an installation. Therefore, the kicker is installed upstream of 309 at ~44^o phase advance from the Lambertson at 308. Due to the reduced phase advance, the kicker strength is about a factor of 2 stronger than if it was at the ideal location. In order to achieve the proper position and angle at the kicker, the MI Lambertson magnet needs also to be rolled so that the injected beam would be at the appropriate angle at the Lambertson magnet to produce the correct angle at the 309 kicker.



(a) SS30LB



(b) SS30_FODO

Figure 18: Beta-functions of Recycler 30 straight section

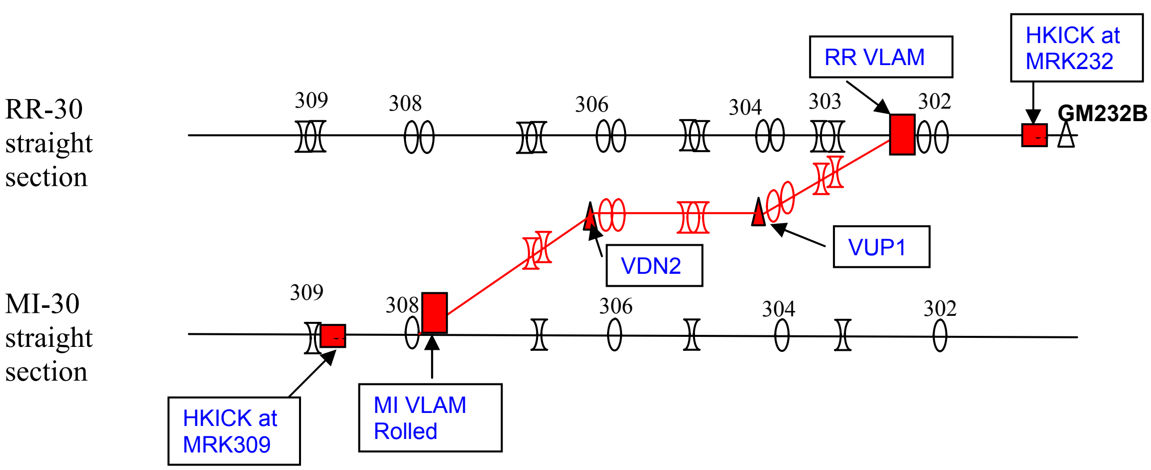


Figure 19: Cartoon of the extraction line from RR to MI

Figure 18a and Figure 18b give the plot of the lattice functions output from MAD and the corresponding beam size respectively. The beam size is calculated as equation (1), but the maximum momentum deviation: $\delta=\Delta p/p=1.2\times 10\text{-}3$(in case of stage 2). Table 8 lists the requirements for the magnets to be used for the injection line.

Magnets to be Used	Type	Length (m)	Number required	θ (mrad)	Tilt (rad)	B_o (kG)	B_1 (kG/m)	Current (Amp)
RRKICK	K232	1.4	3	0.536836	0	0.159	-	
RRLAM	RR-214	4.064	1	23	π/2	1.687	-	
MILAM	ILA	4.064	1	23	-π/2	1.687	-	
VUP1[1)]	ADCW	1.524	1	23	-π/2	9.183	-	478
VDN2[1)]	ADCW	1.524	1	23	π/2	9.183	-	478
QR3031 QR3032	RQMD	0.508	2	-	-	-	-28.7653	-
QR3041	RQMF	0.508	1	-	-	-	27.8711	-
QR3042	RQMF	0.508	1	-	-	-	21.2459	-
QR3051 QR3052	RQMD	0.508	2	-	-	-	-29.6501	-
QR3061	RQMF	0.508	1	-	-	-	24.3667	-
QR3062	RQMF	0.508	1	-	-	-	27.8708	-
QR3071	RQMD	0.508	1	-	-	-	-29.6501	-
QR3072	RQMD	0.508	1	-	-	-	-28.4196	-
VTR303 VTR305 VTR307	VDC		3					5
VHR304 VHR306	HDC		2					5

Table 8: listed the requirement of the magnets to be used for the RR->MI extraction line.

2.2.4 Design and Construction of Injection and Extraction Kickers

There are 5 new kicker systems for this project. They are:

1. Recycler Injection Kicker: located at RR104
2. Recycler Gap Clearing Kicker: located at RR400
3. Recycler Abort Kicker: located at RR400
4. Recycler Extraction Kicker: located at RR232
5. Main Injector Injection Kicker: located at MI309

The first two systems have similar specifications. They have fast rise times (38 nsec – 2 52.809 MHz buckets), 1.55 μsec flattop (82 52.809 MHz buckets), fast fall times (38 nsec – 2 52.809 MHz buckets) to cleanly kick incoming booster batches without affecting circulating beam in the Recycler Ring. The gap-clearing kicker is to clean beam out of the injection gap, which arise from losses in the slip stacking process, into the abort line so that the injection kicker does not kick that beam into nearby magnets. These specifications require a new kicker magnet design.

The injector kicker system will be built on the model of the current MI kicker magnets and the current Tevatron injection kicker pulser. It will have a magnetic aperture of 53 mm x 107 mm (to meet the beam aperture of 33 mm x 81 mm), a fill time of 20nsec, a pulser voltage rise time (1% to 99%) of a little less than 20nsec and a Zo of 50 ohms. With these design parameters the physical length per magnet is 0.8 meters with a magnetic length of 0.4 meters. This magnet will have a nominal B field of 120 Gauss with a nominal current of 500A. In order to get the required 0.301 kG-m, you will need 6.27 magnets and thus we propose a 7 magnet/pulser system to give some tuning range for the main deflection.

This system is expected to need a "bumper" magnet to cancel the tail and allow the system to meet the fall time requirement. We do not have an engineered solution to accomplish the cancellation at this point. We feel that it would be prudent to plan on 2 additional magnets to accomplish this "bumper" function.

Therefore, the tunnel length required for this system is 7 + 2 times 0.8 meters or 7.2 meters (23.6 feet).

The abort, extraction, and injection kickers all have 1.62 μsec (86 52.809 MHz buckets) rise times and 9.51 μsec (502 52.809 MHz buckets) flattop. We can make use of an existing kicker magnet design (the current RR extraction kicker) with a new power supply to meet the specifications for the abort and extraction kickers. The aperture requirements for the injection kicker require a new kicker magnet design.

The abort and extraction kicker systems will require a long pulse (~9.5usec) with a fairly long rise time (~1.6usec). We would propose using the existing 25 ohm recycler transmission line magnets that are currently in use for the transfer lines with a 1.6 usec flat top. Each magnet has an insertion length of 1.8 meters (70 inches) and a magnetic length of 1.4 meters (54 inches). The magnet aperture of these existing kicker magnets is again 53 mm x 107 mm to meet the beam aperture of 33 mm x 81 mm.

The MI injection kicker system will require a long pulse (~9.5usec) with a fairly long rise time (~1.6usec). There are no existing kicker magnets or ceramic vacuum chambers that meet the aperture requirement of 50 mm V x 70 mm H. The magnetic aperture of these kicker magnets must be ~70 mm x 119 mm to meet beam aperture requirements. We propose using 3 newly designed magnets for the kick. We would put the magnets in series with a single PFL pulser, the same as the abort and extraction kicker pulsers. Each system requires one magnet and has an insertion length of 1.55 meters (61 inches) and a magnetic length of 1.14 meters (45 inches).

This system is expected to need two "bumper" systems to cancel the tail and allow the system to meet the fall time requirement. We would plan to use 2 additional magnets to accomplish this "bumper" function. Therefore, the tunnel length required for this system is 3 + 2 times 1.55 meters or 7.8 meters (25.4 feet).

2.2.5 Rework RR-30 Straight Section

The RR 30 Straight Section currently has a special purpose lattice insert for electron cooling of anti-protons. We plan on rebuilding the RR 30 straight to match the standard FODO cells in the rest of the ring. This task includes the design of the lattice and the installation of the magnets. There are 15 permanent magnet quadrupoles needed for this section. We will make use of a subset of the 38 magnets removed (see Section "Removal of ECool") from the electron-cooling insert. These 15 magnets will be refurbished by the Technical Division and installed in the ring.

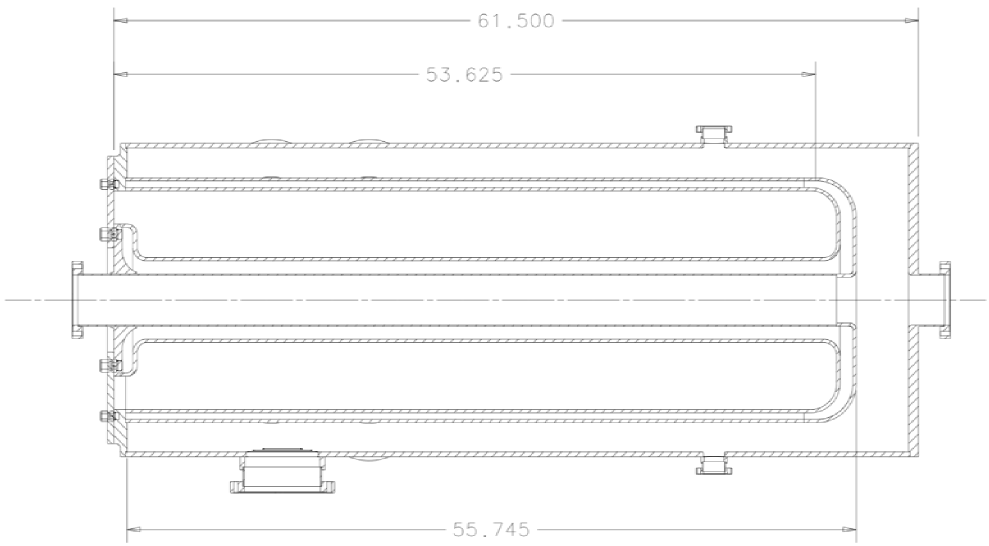
2.2.6 53 MHz RF System

The existing broadband RF system in the Recycler Ring will not be removed. For Proton Plan 2 operation, new RF systems are required. Proton Plan 2 requires a new 53 MHz RF system. For bucket-to-bucket transfers from the Booster and to the Main Injector, the required frequency is 52.809 MHz. For slip stacking, a tunable frequency range of ± 5 kHz and total voltage of 300 kV is necessary. Fast cavity tuning (for beam loading compensation) and higher mode dampers on the cavities are also required.

We propose to build 4 new RF cavities, two of which are necessary for Proton Plan 2 slip stacking and two for SNuMI 53 MHz capture. As they are the same cavity design, we plan on constructing and installing all 4 during the Proton Plan 2 installation period. We plan on recycling the 53 MHz power amplifiers and modulators from the Tevatron RF systems.

2.2.6.1 Specifics of the design

The cavity is a $\lambda/4$ coaxial design with a 25" outer diameter made of OFHC copper with a step-up ratio of 6:1. The central frequency is 52.809 MHz with a Q of ~7000. By using fast garnet phase shifters developed for the Proton Driver [32], the cavity is tunable over a ± 10 kHz range. The shunt capacity is 140 kΩ, leading to 80 kW/cavity at 150 kV. R/Q is 20 Ω. The tetrode anode power dissipation with 1 A of DC beam current and no detuning is 130 kW, while the PA tubes are rated for 150 kW. Higher order mode dampers for the 3^{rd} and 5^{th} harmonic are included in the design. A cross sectional view of the cavity can be seen in Figure 20 and a 3D view in Figure 21.



Created: 11:22:10 on 08-09-06 (D-M-Y) By: rstewart State: 1-INITIAL

Figure 20: Cross sectional view of RF cavity.

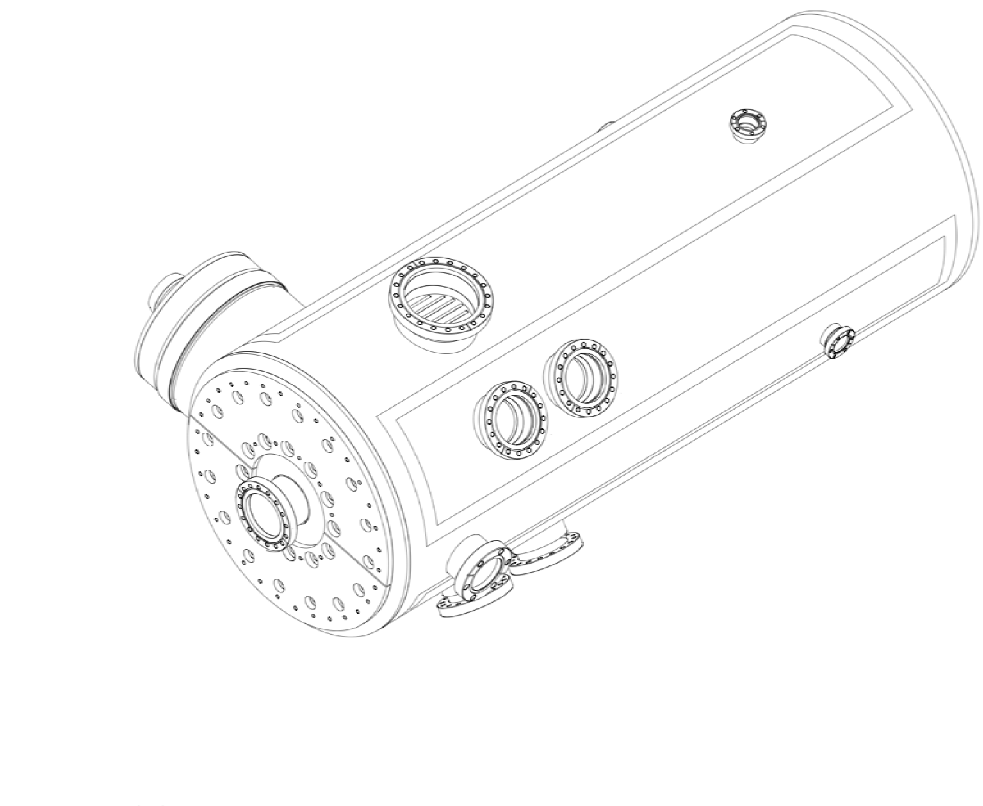


Figure 21: 3D view of RF cavity

2.2.7 Instrumentation

Instrumentation needs for the Recycler Ring can be broken down into three types of systems:

- Position (orbit) measurements: BPMs and multiwires
- Intensity measurements: DCCT and toroids
- Dampers

All of these systems need significant upgrades for the Proton Plan 2 era.

2.2.7.1 BPMs

The current Recycler Ring BPM system uses resonant pickups and electronics at 2.5 MHz. We will upgrade to a 53 MHz system, modeled on the Main Injector BPM system[26]. While the pickups work well at this frequency, the signal cables from the tunnel to the service buildings do not. We need to pull new cables and purchase the associated transition boards for each BPM (216 in total) and reuse the existing EchoTek digitizers.

---

[26] See the documents associated with MI BPM requirements in the BeamsDoc Database, event id = 29 (https://beamdocs.fnal.gov/AD-private/DocDB/ListBy?eventid=29&mode=conference).

We have chosen to use a LMR-195 cable. The total cable length is more than 275,000 feet.

With this amount of additional cable, we have investigated penetrations and cable tray space. We will need to make use of the service building kicker room penetrations, which are available at each service building.

For position measurements in the transfer lines, we will have both BPMs and multiwires. We will be moving the physical BPMs and mulitwires from the current transfer lines to the new transfer lines and pull new cables for both types of instrument.

2.2.7.2 Intensity measurements

We will install a new DCCT for the Recycler Ring. We are currently investigating with the Instrumentation Department the choice between a commercial product (the Recycler currently has a Bergosz DCCT) or an in house design (like the Main Injector DCCT). For the transfer lines, we will move existing Pearson toroids.

2.2.7.3 Dampers

We anticipate that we will need both longitudinal and transverse dampers at the intensity of 6e13 protons. For the longitudinal system, we believe that the current pickups, kickers, and power amplifiers are adequate for our needs. For the transverse systems, the pickups and kickers are adequate but we will need to purchase 5 additional power amplifiers.

2.2.8 Infrastructure

2.2.8.1 New Buildings

To support the Proton Plan 2 upgrades, new facilities are required to house kicker power supplies for the gap clearing kicker near Q400 and for the injection kicker near Q104, to provide connections for these supplies to the Main Injector enclosure, and to house an additional anode power supply at the MI-60 Service Building.

The new facilities will require site utilities, access from existing road system, and must meet applicable codes. To offset the space of new construction, Fermilab facilities will need to be identified to be demolished as the new space is built. Figure 22 shows the general location of the proposed facilities.

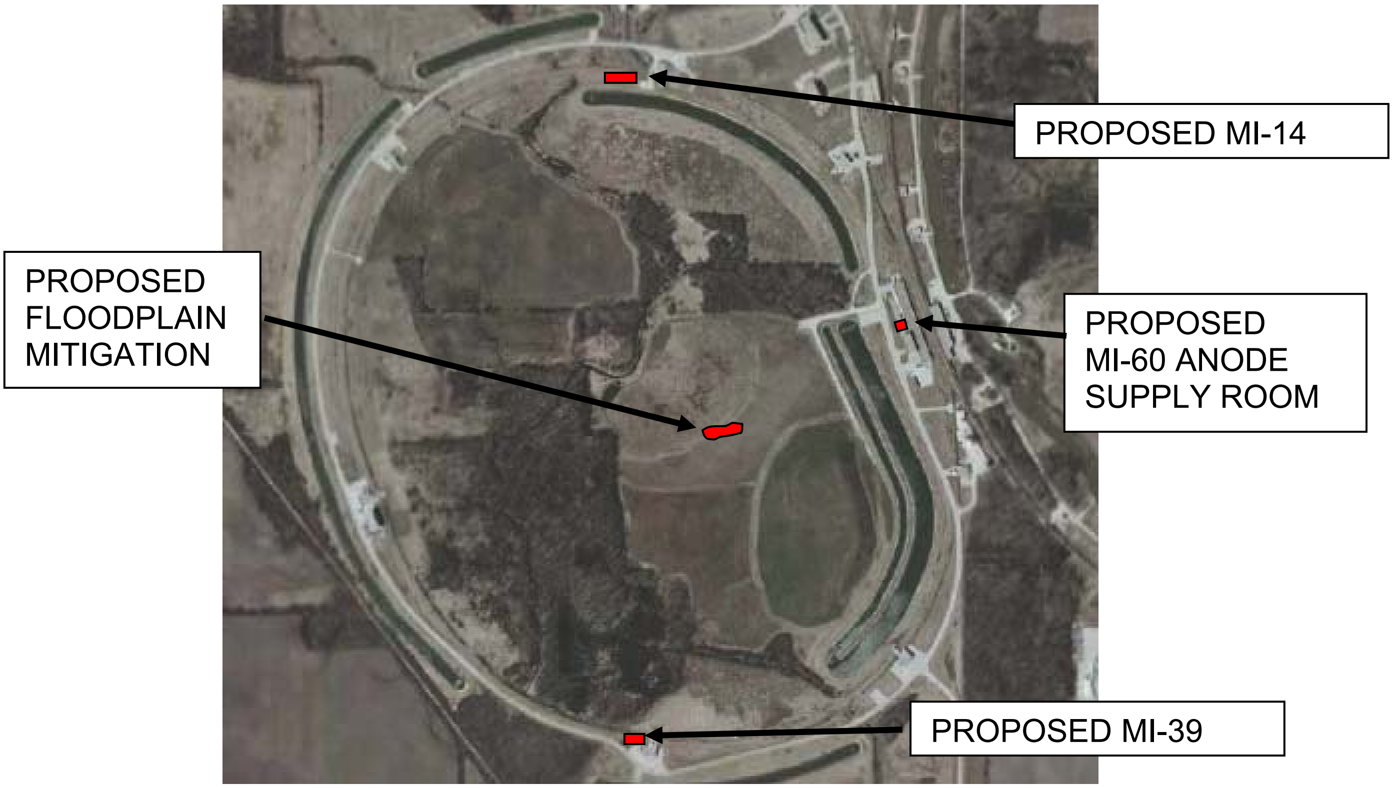


Figure 22: General location of proposed facilities

2.2.8.1.1 Space Management Requirements

Beginning in FY 2003, all new DOE Office of Science funded construction projects which provide new space, must have an equivalent amount of excess space demolished in the year the new facility is occupied.

This project includes funding for the elimination of existing Fermilab square footage equal to the new space. The area demolition requirements are currently expected to be

MI14 (75' x 30')	2250 sf
MI39 (50' x 30')	1500 sf
MI 60 anode supply room (10' x 25')	<u>250 sf</u>
	4000 sf

The costs associated with demolishing currently identified unneeded facilities on the Fermilab site are $80/sf.

2.2.8.1.2 MI-14 Service Building

This building will house kicker supplies and power supplies for new kicker magnets in the region of Q104. The existing MI-10 Service Building has insufficient room to house this new equipment, and it is too far physically from the required location in the Main Injector for the cable lengths to the enclosure. Thus, a new building needs to be constructed.

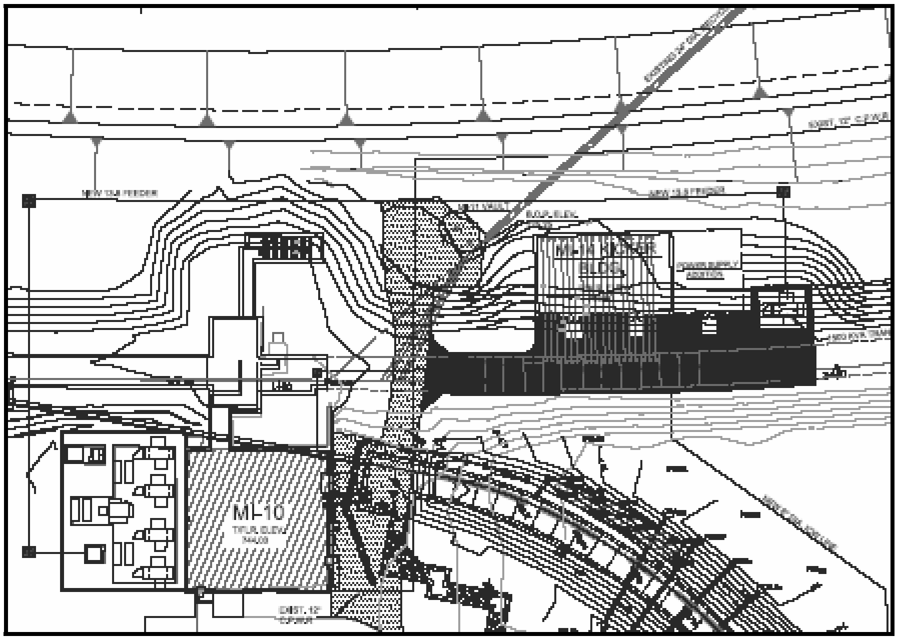


Figure 23: Proposed MI-14 Service Building

The location of the building will be on the inside of the Main Injector enclosure ring, due to the existing Mini-BooNE extraction line located on the outside of the ring in this area. The building will be positioned between the berm and the pond, requiring the access to the building from a new road to be built on top of the berm.

The building will sit in the floodplain, hence the floor elevation will need to be 746.0', which is 2 ft above the 100 year flood level. Also, compensatory storage of approximately 11,200 cf for flood will need to be developed inside the Main Injector ring near the existing mitigated wetlands area to replace the area being removed for the building.

The function of the kicker supply portion of the building is very similar to the F-17 Service Building, hence the design has been based on that facility. The power supply room portion of the building has been set at 50% of the kicker supply space. The criteria for this facility are:

- One story building with 11.5' clear height
- 1-ton hoist to be supported from roof beams
- Depressed floor for 30'x 50' kicker room to contain oil from equipment to mitigate spills
- 30' x 25' power supply room
- Oil-resistant coating on concrete floor
- 16 – 6" conduit penetrations from building to MI enclosure for 8 known and 8 future cable runs for kicker room
- 6-6" conduit penetrations from building to MI enclosure for power supply room
- Straight 6" penetration to MI enclosure for 1.5" LCW supply and return piping, with both pipes in same conduit. Anticipating heat rejection to LCW is 50 kW

- Two 5 inch "straight shot" conduits to the tunnel for installing fluorinert cooling system
- Building power: new 750 kVA , 13.8kV – 480/277V beamline power transformer located adjacent to the building. New 15kV air switch at MI-10 service building, with existing 15kV feeders 96//97 extended from MI-8 Service Building via existing MI ductbank. New 225A, 480/277V feed from MI-10 Service Building to power fluorinert pumps (480V), kicker power supplies, electronics racks, and miscellaneous building loads.
  - Kicker power requirements: Approximately 30 kVA, 208V power with dedicated 45kVA shielded transformer and panelboard
  - Power supply power requirements: 3 Spang power supplies and switching power supply @ 125A, 480V service to each.
  - Electronics racks: Approximately 10 racks with 2-20A, IP, 120V branch circuits to each.
- Communications/controls to be supplied from MI-10 via new ductbank to MI-14
- ICW supply/return from main distribution along Indian Creek Road to serve for fire suppression
- Concrete masonry wall separating power supply and kicker rooms
- Two sets of double doors for entrance into kicker room from outside, with a removable panel at the top of the doors for infrequent loading of tall equipment. Aprons in front of the building should extend 8' from door.
- One overhead and one single mandoor from outside into power supply room
- Air conditioning and unit heaters serving each of the 2 rooms
- Two 18" cable trays in ceiling of MI enclosure for likely 32 cables to kicker magnets, with maximum 200 ft length of cable from equipment in building to equipment in tunnel

Preliminary drawings for site layout and cross-section, as well as the floodplain mitigation, can be found in Document 62 in the Proton Plan 2 Documentation database (DocDB).

2.2.8.1.3 MI-39 Service Building

This building will house kicker supplies for new kicker magnets in the region of Q400. The existing MI-40 Service Building has insufficient room to house this new equipment, and it is too far physically from the required location in the Main Injector for the cable lengths to the enclosure. Thus, a new building needs to be constructed.

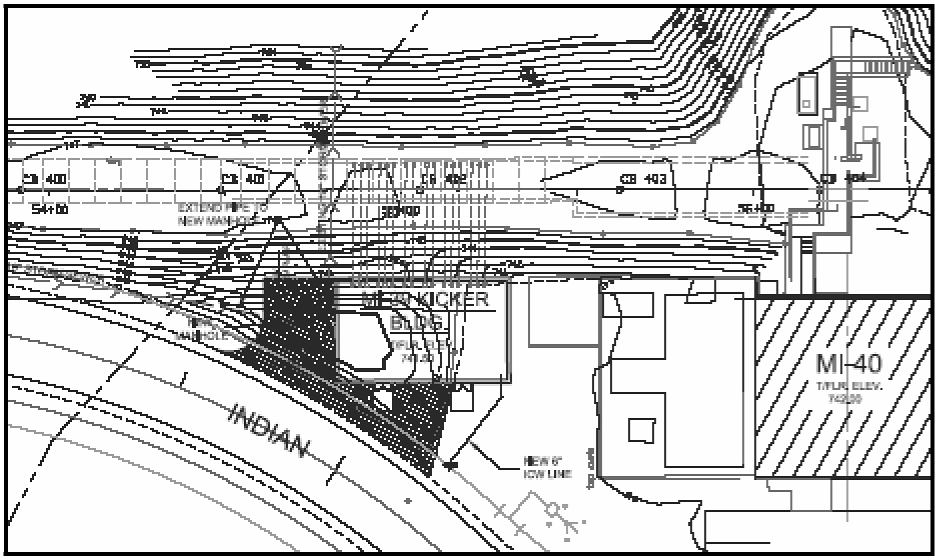


Figure 24: Proposed MI-39 Service Building

The building is sited on the south side of the MI enclosure because of the wetlands known to exist in this area and because the berm is very high. The building would need to be built on piers to bring it up to an accessible grade. Positioning the building on the south side of the enclosure constrains the site by the enclosure to the north and west, existing Indian Creek Road to the south, and the existing MI-40 substation to the east. The area can be accommodated if the existing drainage swale and culvert is replaced with a catch basin that connects culvert pipes, and the area filled in. Vehicle access into the building will be via new hardstand adjacent to the existing road. Maintenance access to the berm would be via the new hardstand and ramp to the west of the building.

The function of MI-39 would be very similar to the F-17 Service Building; hence the design has been based on that facility. The criteria for this facility are:

- One story building with 11.5’ clear height
- 1-ton hoist to be supported from roof beams
- Depressed floor in 30’ x 50’ building to contain oil from equipment to mitigate spills
- Oil-resistant coating on concrete floor
- 16 – 6” conduit penetrations from building to MI enclosure for 8 known and 8 future cable runs
- Straight 6” penetration to MI enclosure for 1.5” LCW supply and return piping, with both pipes in same conduit. Anticipating heat rejection to LCW is 50 kW
- Two 5 inch "straight shot" conduits to the tunnel for installing fluorinert cooling system
- Building power: new 225A, 480/277V feed from MI-40 Service Building to power fluorinert pumps (480V), kicker power supplies, electronics racks, and miscellaneous building loads.
    - Kicker power requirements: Approximately 30 kVA, 208V power with dedicated 45kVA shielded transformer and panelboard

    - Electronics racks: Approximately 10 racks with 2-20A, IP, 120V branch circuits to each.
- Communications/controls to be supplied from MI-40 via new ductbank to MI-39
- ICW supply/return from main distribution along Indian Creek Road to serve for fire suppression
- Two sets of double doors for entrance from outside, with a removable panel at the top of the doors for infrequent loading of tall equipment. Aprons in front of the building should extend 8' from door.
- Air conditioning and unit heating
- Two 18" cable trays in ceiling of MI enclosure for likely 32 cables to kicker magnets, with maximum 200 ft length of cable from equipment in building to equipment in tunnel

Preliminary drawings for site layout and cross-section can be found in Document 62 in the Proton Plan 2 Documentation database (DocDB).

2.2.8.1.4 MI-60 Anode Supply Room

There is a requirement for a fourth anode supply room at MI-60. Six more RF systems (two more in the Main Injector Ring and four in the Recycler Ring) are to be added to the existing eighteen RF systems. This addition increases the number of RF systems by one third, raising the number of anode supplies from three to four. The functionality of the fourth (or additional) anode supply is identical to the existing three anode supplies, so the space and enclosure requirements are also identical.

The fourth anode supply room will be constructed in the same manner as the other 3 existing anode supply rooms at MI-60. The open site to the north of the existing high bay and south of the adjacent anode supply room is sufficient in area, but requires creation of a fire wall at the north side of the high bay to comply with requirements of NFPA 850.

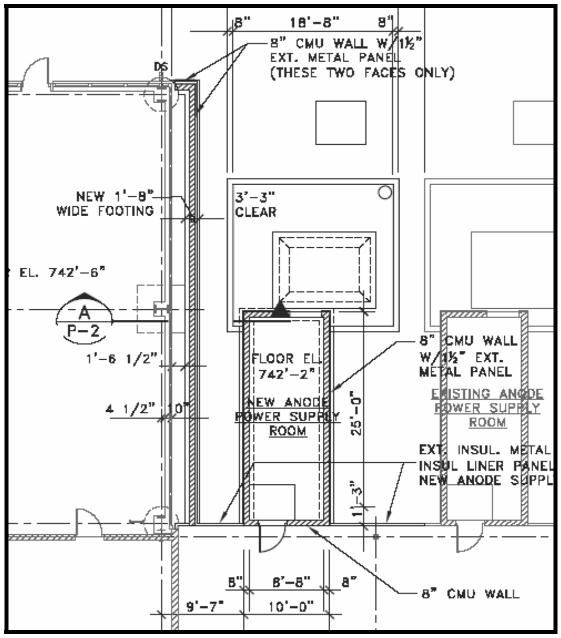


Figure 25: Proposed MI-60 Anode Supply Room

The firewall will consist of leaving the existing siding and windows in place while constructing an 8” concrete masonry wall to the north, then roofing over the cavity in between new and existing. Finally, siding to match the existing building will cover the masonry.

The anode supply room will be 10’ x 25’ in area, with a new transformer pad and containment and a new switch pad. Existing transformer and switch will be moved from F-0 for reuse in this location. The room will have lights, dedicated air-cooling, and power similar to the existing rooms. A door will be installed from the west wall of MI-60 into the new room. The room will be lined with steel sheets on the ceiling, floor, and sides, to provide a continuously grounded Faraday cage in the case of any arcing of the anode supply components.

Preliminary drawings for construction related to the new anode supply room can be found in Document 62 in the Proton Plan 2 Documentation database (DocDB)

2.2.8.2 Risk

While the design of the conventional facilities has been progressed to a point where a cost and schedule range can be estimated, details of the design are still evolving. This process will continue in the coming months.

The site and subsurface conditions present a cost and schedule risk. This risk will be mitigated by performing subsurface investigation with soil borings at MI-14 and MI-39 to better understand the conditions and their impact on the planned construction.

The execution of the penetrations work during an accelerator shutdown presents a schedule risk, as the current task duration has no schedule contingency with respect to the anticipated shutdown length. During final design, methods to create concurrent tasks or provide contractual means to complete the work early will be explored to reduce the schedule risk.

2.2.8.3 Value Management

No formal value management studies are anticipated for this scope of work. However, alternative locations to the currently proposed sitings of MI-14 and MI-39 Service Buildings were explored during early conceptual design, to lessen the impact of building in wetlands or floodplain, and to create reasonable vehicle access to the buildings. During final design, optimization of penetration routings and locations in the existing tunnel will be explored.

2.2.8.4 Schedule

The construction work goal is to complete Service Buildings MI-14 and MI-39 in time to allow them to be used for assembly and testing of the Recycler injection kicker by end of summer 2008. The work to install the penetrations at these two locations requires an accelerator shutdown. Procurement assumptions include accomplishing the installation of the penetrations to bring them outside the radiation shielding area in summer 2007 so that the building construction can happen without an accelerator shutdown during the construction season of 2008. It is assumed both sets of penetrations would be installed simultaneously under one contract. In addition, for economies of scale, it is assumed that all three building construction subprojects would be executed in one construction project, even though the MI-60 Anode Supply Room may not be required as early as the other buildings.

A proposed schedule to meet these requirements is shown in Figure 26.

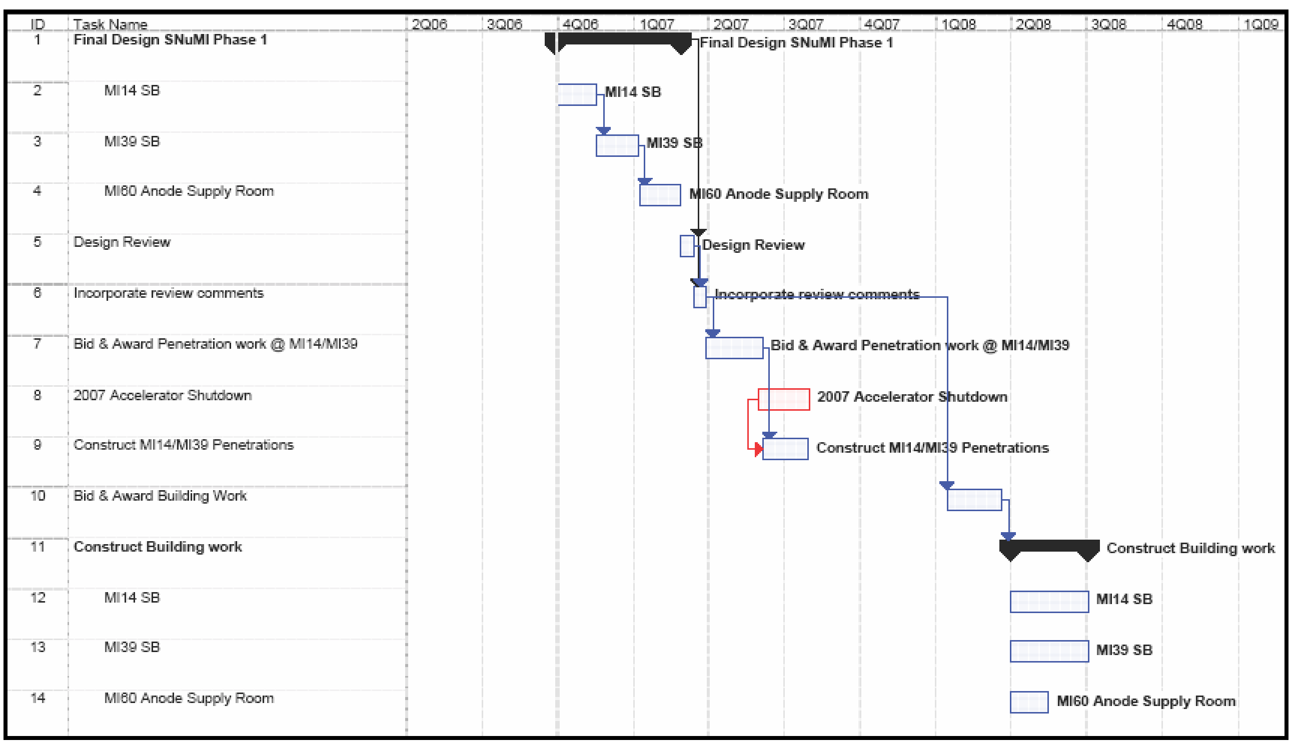


Figure 26: Proposed Design/Procure/Construct Schedule

2.2.9 References

32.“The Proton Driver Design Study”, Fermilab-TM-2136, December 2000.

2.3 Main Injector Upgrades (WBS 1.3)

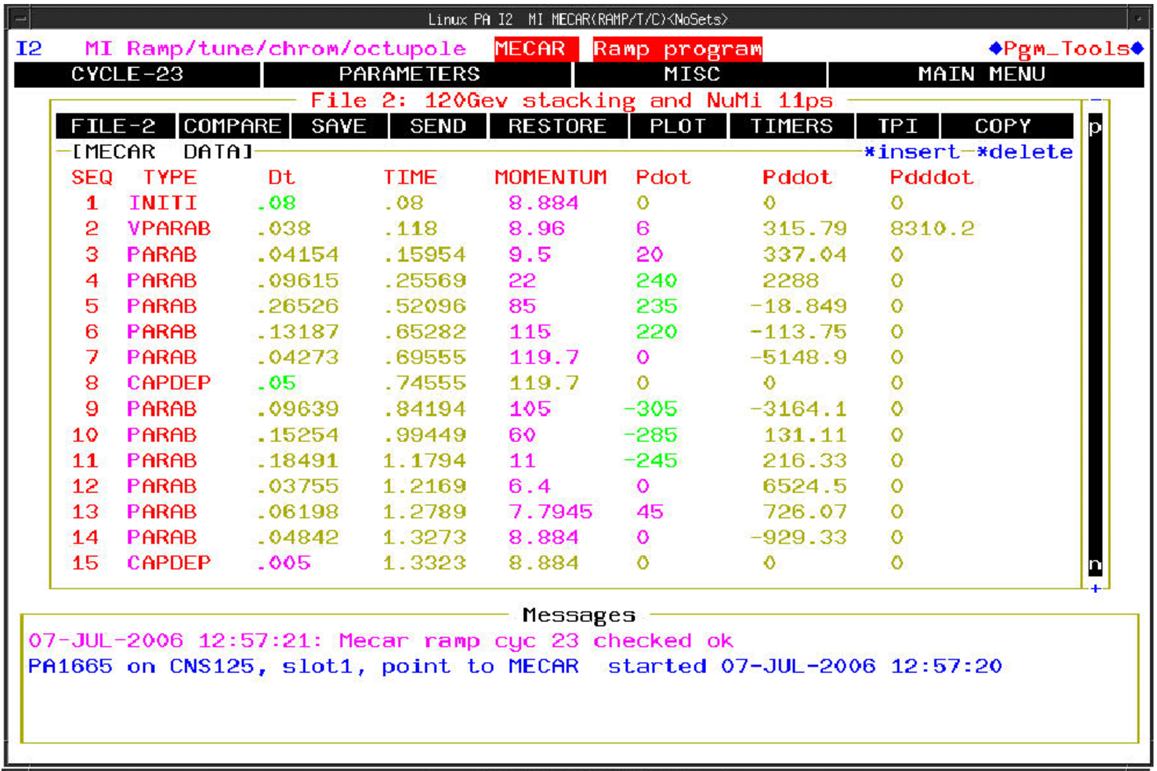
2.3.1 Introduction

For Proton Plan 2, the Main Injector will be accelerating almost the same proton intensity as in Proton Plan 1 (4.9E13 ppp instead of 4.5E13 ppp). The beam power out of Main Injector is much larger (700KW instead of 400KW) mainly because the cycle time is reduced from 2.2 sec to 1.33 sec. This cycle reduction is mainly achieved by using the Recycler Ring for stacking but also requires increasing the maximum acceleration rate in Main Injector from 204 GeV/sec to 240 GeV/sec. In order to accommodate the faster ramp, one of the quad power supplies needs to be upgraded and two extra RF stations need to be installed.

The existing MI40 absorber is fully compatible with Proton Plan 2, as recently verified with MARS15 calculations in [35]. Up to 3.63×10^{19} protons @ 150 GeV/year can be sent to the MI40 beam absorber without contaminating the ground or surface waters. Thermal considerations would allow up to 1.28MW of beam power to be dumped in the MI40 absorber.

2.3.2 Main Injector ramps

In order to reduce the Main Injector 120 GeV cycle time for Proton Plan 2 to 1.33 sec, the maximum acceleration rate has to be increased from 205 GeV/sec to 240 GeV/sec. The current 120 GeV ramp used for the mixed mode Slip stacking and NuMI along with the Proton Plan 2 proposed ramp is shown in Figure 27. The current Main Injector 120 GeV ramp has a 488 msec dwell at injection in order to accommodate the slip stacking for pbar stacking and five injections for NuMI. This dwell time is reduced to 80 msec for Proton Plan 2 since we only have one injection per cycle from Recycler.



Linux PA I2 MI MECAR(RAMP/T/C)<NoSets>

I2 MI Ramp/tune/chrom/octupole MECAR Ramp program ◆Pgm_Tools◆

CYCLE-23 | PARAMETERS | MISC | MAIN MENU

File 2: 120Gev stacking and NuMi 11ps

FILE-2 | COMPARE | SAVE | SEND | RESTORE | PLOT | TIMERS | TPI | COPY

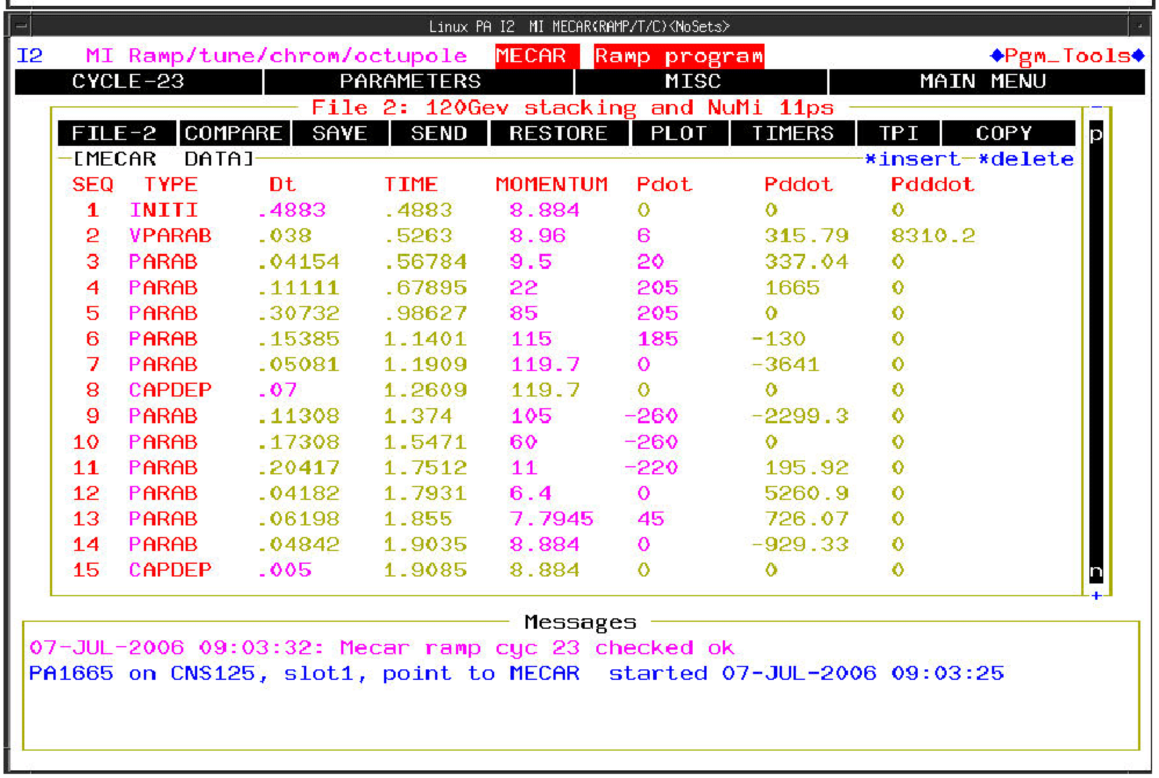
[MECAR DATA] *insert *delete

SEQ	TYPE	Dt	TIME	MOMENTUM	Pdot	Pddot	Pdddot
1	INITI	.08	.08	8.884	0	0	0
2	VPARAB	.038	.118	8.96	6	315.79	8310.2
3	PARAB	.04154	.15954	9.5	20	337.04	0
4	PARAB	.09615	.25569	22	240	2288	0
5	PARAB	.26526	.52096	85	235	-18.849	0
6	PARAB	.13187	.65282	115	220	-113.75	0
7	PARAB	.04273	.69555	119.7	0	-5148.9	0
8	CAPDEP	.05	.74555	119.7	0	0	0
9	PARAB	.09639	.84194	105	-305	-3164.1	0
10	PARAB	.15254	.99449	60	-285	131.11	0
11	PARAB	.18491	1.1794	11	-245	216.33	0
12	PARAB	.03755	1.2169	6.4	0	6524.5	0
13	PARAB	.06198	1.2789	7.7945	45	726.07	0
14	PARAB	.04842	1.3273	8.884	0	-929.33	0
15	CAPDEP	.005	1.3323	8.884	0	0	0

Messages

07-JUL-2006 12:57:21: Mecar ramp cyc 23 checked ok

PA1665 on CNS125, slot1, point to MECAR started 07-JUL-2006 12:57:20



Linux PA I2 MI MECAR(RAMP/T/C)<NoSets>

I2 MI Ramp/tune/chrom/octupole MECAR Ramp program ◆Pgm_Tools◆

CYCLE-23 | PARAMETERS | MISC | MAIN MENU

File 2: 120Gev stacking and NuMi 11ps

FILE-2 | COMPARE | SAVE | SEND | RESTORE | PLOT | TIMERS | TPI | COPY

[MECAR DATA] *insert *delete

SEQ	TYPE	Dt	TIME	MOMENTUM	Pdot	Pddot	Pdddot
1	INITI	.4883	.4883	8.884	0	0	0
2	VPARAB	.038	.5263	8.96	6	315.79	8310.2
3	PARAB	.04154	.56784	9.5	20	337.04	0
4	PARAB	.11111	.67895	22	205	1665	0
5	PARAB	.30732	.98627	85	205	0	0
6	PARAB	.15385	1.1401	115	185	-130	0
7	PARAB	.05081	1.1909	119.7	0	-3641	0
8	CAPDEP	.07	1.2609	119.7	0	0	0
9	PARAB	.11308	1.374	105	-260	-2299.3	0
10	PARAB	.17308	1.5471	60	-260	0	0
11	PARAB	.20417	1.7512	11	-220	195.92	0
12	PARAB	.04182	1.7931	6.4	0	5260.9	0
13	PARAB	.06198	1.855	7.7945	45	726.07	0
14	PARAB	.04842	1.9035	8.884	0	-929.33	0
15	CAPDEP	.005	1.9085	8.884	0	0	0

Messages

07-JUL-2006 09:03:32: Mecar ramp cyc 23 checked ok

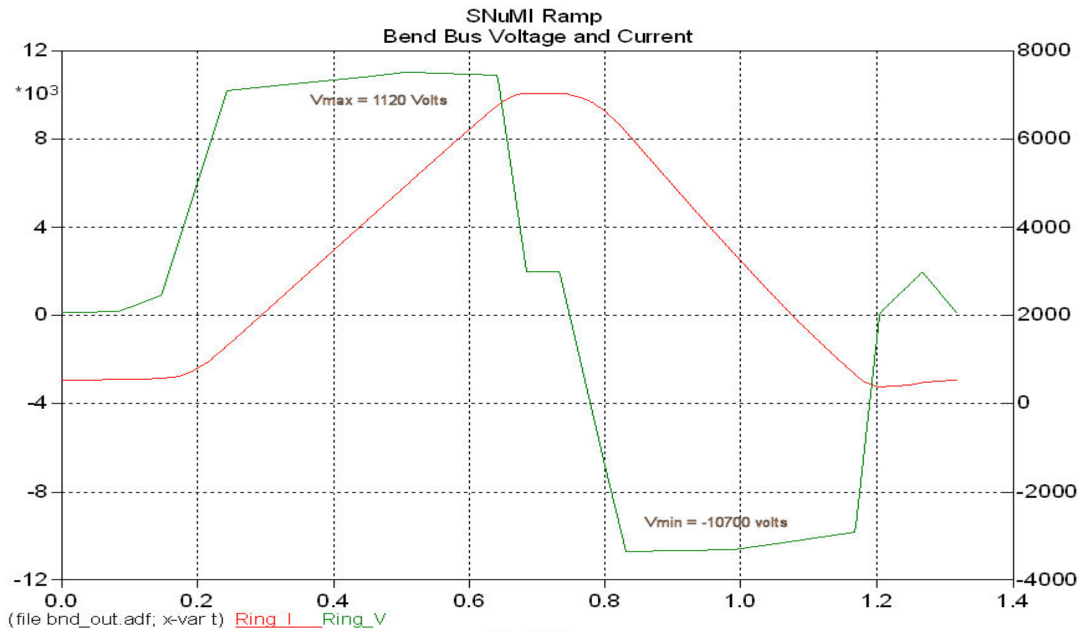
PA1665 on CNS125, slot1, point to MECAR started 07-JUL-2006 09:03:25

Figure 27: Current 120 GeV Main Injector ramp (bottom) and Proton Plan 2 ramp (top).

The voltages and currents for the Main Injector Bend and the two Quad Buses during the Proton Plan 2 ramp are shown in Fig. 2. The max voltage available in the main bending bus is 11.8 KV, while the voltage available for the horizontal and vertical quad busses is 3.2 and 2.8 KV respectively.

As can be seen from Figure 28, during the Proton Plan 2 ramp we are going to exceed the maximum available voltage of the defocusing (vertical) bus. For this we propose to increase the available voltage at the defocusing bus by replacing one of the transformers with a higher voltage one and modifying the corresponding supply. These changes will make the available voltage from the defocusing bus equal to the focusing one.

The RMS current for the Main Injector dipoles and quads for the Proton Plan 2 ramp has been calculated to be 4000 A and 1600 A respectively. These numbers are lower than the values of 5000 A and 2000 A that the Main Injector water-cooling system was designed to handle. For comparison the RMS current values for the present Main Injector $23 ramp are 3550 A and 1425 A.



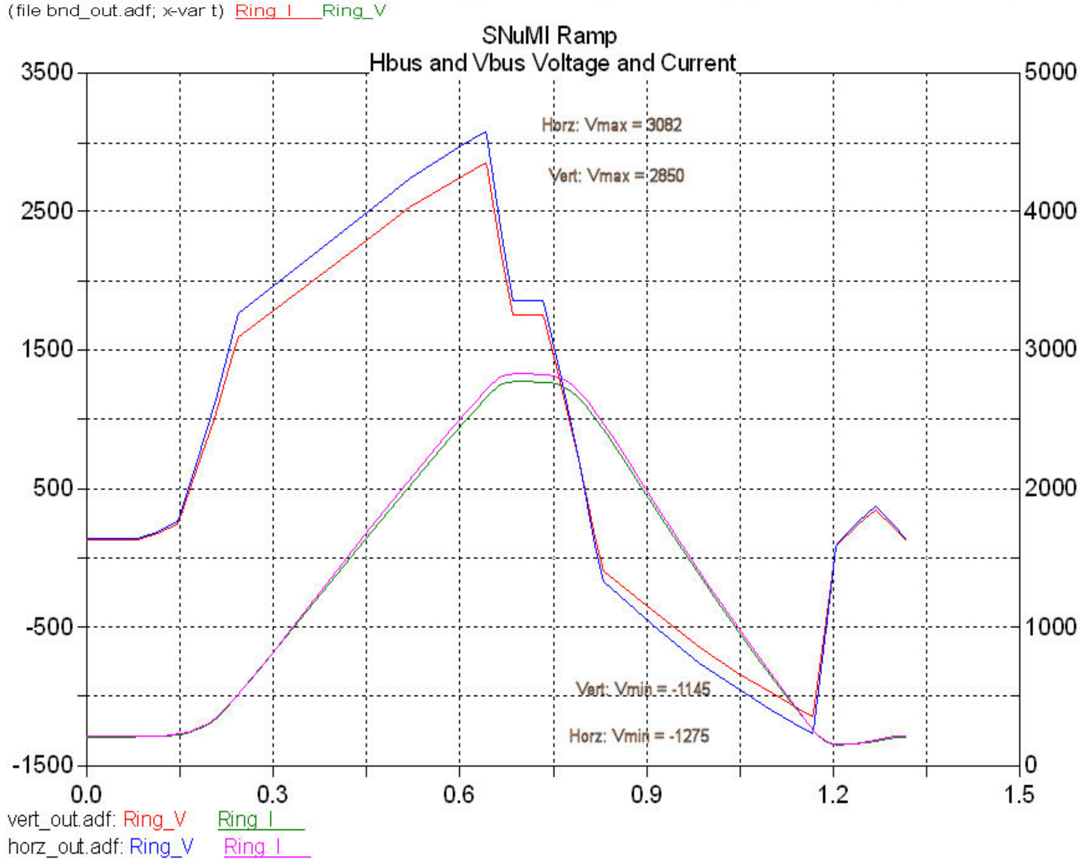


Figure 28: Voltages and currents for the bend bus (top) and the two quad busses (bottom) during the Proton Plan 2 ramp.

2.3.3 Main Injector RF Cavities

The current Main Injector RF system consists of 18 stations providing a maximum acceleration voltage of 240 KV and 175 KW per station. It has enough power to accelerate up to 5.5E13 protons with 240 GeV/sec.

The moving bucket area available after transition is a function of the acceleration rate and the max. rf voltage available. For a fixed RF voltage and acceleration rate the bucket area has a minimum at $\sqrt{3}$ times the transition energy. In the Main Injector we have found that we need a moving bucket area after transition of at least 1.8 eV-sec with slipped stacked beam in order to avoid beam losses. From Figure 29 we can see that with 18 rf stations we cannot produce a sufficiently large enough bucket area to efficiently accelerate slipped stacked beam faster than 240 GeV/sec. Since we have a total of 3 spare cavities we propose to install two extra cavities in Main Injector in order to have enough extra voltage for running with 240 GeV/sec reliably (even with a station down). Those cavities are going to be installed at the "phantom" locations 4A and 14A. Most of the utilities that we need are available and the penetrations exist. Two new modulators and two bias supplies will need to be fabricated. The most challenging part of this job is the manufacturing and installation of the bus bars for the cavity tuners.

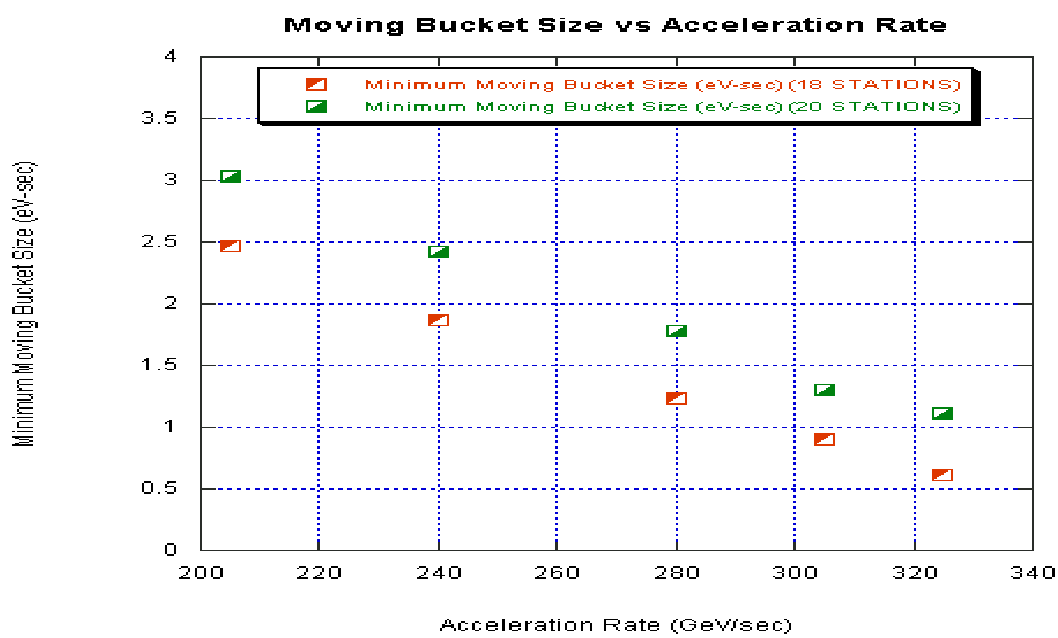


Figure 29: Minimum moving bucket area as a function of acceleration rate for 18, 20 rf stations.

2.3.4 Main Injector Collimators

As part of Proton Plan 1 a two-stage collimation system, comprised of one primary horizontal collimator and four secondary collimators, will be installed during the Summer 07 shutdown. These collimators are designed to intercept the ~5% of the total beam intensity at 8 GeV that is not captured as part of the slip stacking process. These collimators are going to be needed for Proton Plan 2, since most of the uncaptured beam during slip stacking in the Recycler will be transferred to the Main Injector. The collimator design is such that we should be able to collimate up to 5% of the Proton Plan 2 beam.

The position of the collimators in Proton Plan 2 might not be compatible with the proton injection line from the Recycler to the Main Injector proposed for Proton Plan 2. We should be able to reposition any of the collimators that interfere with the injection line.

2.3.5 Decommissioning of the A1 Line

The A1 line used for Pbar transfers from Main Injector to the Tevatron will not be used and needs to be decommissioned. In addition the 3 Lambertson magnets and the kicker used for the Pbar extraction in the Main Injector ring need to be removed since they represent aperture restrictions and are large sources of impedance.

2.3.6 References[27]

33. Daniel Wolff, "MI ramp rates in the SNuMI era" Beams-Doc 2335.
34. Ioanis Kourbanis," Beam Acceleration Capabilities of the present MI RF system", Beams-doc-1927.
35. Nikolai Mokhov,"SNuMI Collimators and Beam Absorbers", Beams-Doc 2266.

2.4 Radiation Safety for the accelerator complex

2.4.1 Introduction

In this chapter, the radiological considerations for operation of the Accelerator Complex for Proton Plan 2 are considered. The scope of the review includes all accelerators beginning with the Linac and proceeding through the Booster, 8 GeV Transfer Line, the Recycler Ring, and the Main Injector. (The radiological concerns for the NuMI beamline are addressed separately in Section 2.5.14.) The analysis contained in this section is based up current requirements of the Fermilab Radiological Controls Manual. This section is considered preliminary; analysis and proposed solutions have not yet been fully reviewed or approved by laboratory safety professionals.

The radiological considerations for all of the above accelerators and beam lines have been considered extensively and are documented in shielding assessments conducted by the Accelerator Division and reviewed and approved by the ES&H Section. In all cases, the shielding assessment for each accelerator and each beam transfer line is used as a starting point in the evaluation which is to follow. Other measurements and verification data available are used where applicable.

The posting and entry control requirements for access to areas outside of beam enclosures where prompt radiation exposure may exist for normal and accident conditions are given in the Fermilab Radiological Controls Manual and are repeated here in Table 9 and Table

---

[27] Names of References do not necessarily reflect the Proton Plan 2, SNuMI name distinctions.

10, respectively. In some instances such as at a beam absorber or target hall, the normal condition may dominate or be equivalent to the worst case condition.

Dose Rate (DR) Under Normal Operating Conditions	Controls
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy.
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 9 Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions

Maximum Dose Equivalent (D) Expected in 1 hour	Controls
D < 1 mrem	No precautions needed.
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy. The Area RSO has the option of imposing additional controls in accordance with the guidance of Article 231 to ensure personnel entry control is maintained.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 10 Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions

The Proton Plan 2 goal is to operate the NuMI target hall at 700 KW beam power or about 1.3E17 protons per hour. To accommodate such operation, the Accelerator Division Beam Safety Permit must be considered. Present Permit limits for the various accelerators in the chain are shown in [38]. For most machines, the Administrative Beam Permit used by the Operations Department is set equal to the DOE approved Beam Safety Envelope. The notable exception is in the Booster where the Beam Permit has been intentionally set less than the Beam Safety Envelope. Two additional limits are imposed upon the Beam Permit. The AD ES&H Department has established an Operating Intensity Limit which is approximately 90% of the Beam Permit. The AD Operations Department imposes a Warning limit on the Operating Intensity Limit. The Warning Limit is the de facto upper level of beam intensity at which beam is operated. In the most conservative of cases, the net effect on the Beam Permit Intensity Limit is that operations are conducted at about 80% of the Beam Permit Intensity Limit. In evaluating the Accelerator complex then, it is necessary to consider the radiological implications of operating 120 GeV accelerators and beam transfer lines at 700KW/0.8 or 875 KW. The beam intensity necessary to be evaluated for all accelerators and beam transfer lines for Proton Plan 2 operation is thus 1.64E17 protons per hour. There is no consideration of additional beam power for other programs in this review. However, excess capacity is identified where it exists. Unresolved shielding issues will be summarized at the end of this section.

There are a fair number of Radiation Safety Systems used in the present configuration of the Accelerator complex. The arrangement of these systems is designed to meet present operational requirements. The Radiation Safety Systems will need to be reviewed and may need to be reconfigured for Proton Plan 2. The configuration of the Radiation Safety Systems will require reevaluation, based upon the new programmatic goals and anticipated operating scenarios.

2.4.2 Machine Shielding Assessments

2.4.2.1 LINAC

The Linac shielding was last assessed in 1993. The Linac Beam Permit is based upon 15 Hz operation with a pulse width of 30 us and amplitude of 35 mA, equivalent to 3.54E17 p/h. The Linac Warning Limit (effective operating limit) is 3.19E17 protons per hour. For Radiation Safety purposes, the LINAC can support 700 KW operation of Proton Plan 2 and could provide up to an additional 1.84E17 protons per hour to other users.

2.4.2.2 Booster

The present Booster Shielding Assessment was completed in April 1999 [39]. The assessment included consideration of the Booster injection line, the Booster accelerator, and the MI8 extraction line up to cell body 803. The upper intensity limit given by the DOE approved Beam Safety Envelope is 1.8E17 protons per hour. The Beam Permit Limit has been set to the programmatic goal of 1.35E17 p/h. Application of safety factors limits the present Booster intensity to 1.09E17 protons per hour, about 84% of the beam power required for Proton Plan 2. It should be an administrative matter to increase the Booster Beam Permit from 1.35E17 protons per hour to 1.8E17 protons per hour without the necessity for additional shielding assessment work. With this change, the Booster accelerator could provide beam for Proton Plan 2 with an additional 9E15 protons per hour available for other users.

2.4.2.3 MI 8 Line

The MI 8 line shielding was evaluated as part of the 1998 MI shielding assessment [43]. The present Beam Permit limit for the MI8 line is 1.35E17 protons per hour. Like the Booster, the limit for the MI8 line was set to meet programmatic goals of the time. The

MI8 line was assessed beginning at cell body 803 through the injection region at MI 10. The MI 8 line shielding is equivalent to at least 24.5 feet throughout the entire length. The magnet to ceiling height in the MI 8 line is about 3 feet through the sections 803 to 810 and about 6 feet for the remainder of the line.

Table 11 shows the required amount of shielding considering the line for unlimited occupancy. The MI 8 line is adequately shielded for 700 KW (Proton Plan 2).

energy	intensity	cycle time (sec)	component to ceiling distance
8	1.64E+17	3600	3
		Required shielding	23.3

Table 11: Shielding requirement for MI 8 line for 700 KW Proton Plan 2 Operation

The Main Injector shielding assessment will need to be revised to allow sufficient 8 GeV beam intensity to support 700 KW NUMI operation (Proton Plan 2). The nature of the revision work would be to apply the present shielding scaling methodology for analysis of 8 GeV shielding. It should be possible to establish a Beam Permit of up to 1.64E17 protons per hour based upon the existing 24.5 feet of shielding over the MI8 line. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined to determine the whether any of them are more limiting than the earth berm shielding. The actual upper limit of the Beam Permit could be set based upon the most limiting feature of the MI8 line.

2.4.2.4 Recycler Ring

The Recycler Ring shielding assessment was originally conducted within the MI shielding assessment in 1998 [43]. The present intensity limit for the Recycler Ring is 1.2E16 protons per hour, so shielding assessment work is required before Proton Plan 2 operation can take place.

Table 12 shows the required shielding for a minimally-occupied, controlled area, the category under which the MI shielding was re-evaluated during an October 2004 shielding assessment [45].

energy	intensity	cycle time (sec)	component to ceiling distance
8	1.64E+17	3600	1
		Required shielding	23.9

Table 12: MI shielding requirement for Recycler Ring operation to support 700 KW Proton Plan 2 operation for a minimally-occupied, controlled area

The shielding design requirement for the Main Injector was 24.5 feet; however, the as-built condition achieved was typically 26 feet. The Recycler Ring shielding should be sufficient if the MI shielding is evaluated as minimally-occupied, controlled area. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined to determine the whether any of them are more limiting than the earth berm shielding.

2.4.2.5 Main Injector

The Main Injector shielding was reviewed and appended in October 2004 [45] in order to provide the incremental increase in beam power to support the NuMI project. In the

October 2004 assessment, the MI shielding berm was evaluated primarily as a minimally-occupied, controlled area. A Safety Assessment of the MI berm included with the latest assessment concludes that Controlled Area posting is not required for minimally-occupied, controlled areas in accordance with the requirements of Article 236 of the FRCM [46]. Some regions of the MI have been posted as Controlled Areas as delineated in Article 236 of the FRCM.

There was some built-in conservatism identified in the 1998 Shielding Assessment, which has, to date, not been considered for the Main Injector. While the magnet to tunnel ceiling distance in the MI beam enclosure is typically 5.5 feet, the shielding was evaluated for a magnet to tunnel ceiling distance of 3 feet. The shielding requirement for 120 GeV operation at 700 KW (Proton Plan 2) considering the actual magnet to tunnel ceiling distance and unlimited occupancy requirements, is shown in Table 13.

energy	intensity	cycle time (sec)	component to ceiling distance
120	1.64E+17	3600	5.5
		Required shielding	24.4

Table 13: MI shielding requirement for 700 KW operation (Proton Plan 2)

The Main Injector shielding design was for a minimum of 24.5 feet. The typical as built shielding thickness achieved was 26 feet. From the forgoing, one may conclude that the shielding is sufficient for 700 KW operation of the Main Injector for Proton Plan 2.

The existing Main Injector shielding assessment (October 2004) will need to be revised for Proton Plan 2 operation. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined, although no issues are foreseen.

2.4.3 Surface Water, Ground Water, Air Activation, and Residual Activation

The activation of surface water, ground water, and air are considered in this section. In general, the activation of air and water associated with the Accelerator complex is well understood. The levels of activation of air and water under present conditions, while measurable, do not approach any State or Federal limits. The levels of water and air activation can be expected to increase by the ratio of the beam power increase required for Proton Plan 2. The anticipated levels of water and air activation for Proton Plan 2 should not pose any restrictions on operation of the Accelerator complex. The specific conditions for each machine in the Accelerator complex are discussed below.

Residual activation of beam line components is an important consideration for a number of reasons. In general, as beam power increases the radiation dose to workers can be expected to increase. In addition, higher levels of activation can lead to reduced lifetime of accelerator components. The efforts to reduce residual activation are discussed below for each machine of the Accelerator complex.

2.4.3.1 LINAC

Since the peak beam energy of the LINAC is 400 MeV and due to the relatively low Linac beam power, the potential for activation of surface water, ground water and air is severely limited.

Residual activation does exist in the Linac beam enclosure and would be expected to increase with higher beam intensity operation to support Proton Plan 2. Attention is given to reducing losses in Linac as part of normal operations. Effort is also underway as part of Proton Plan 1 to improve Linac beam quality through the quadrupole power supply control upgrade. This upgrade should be to improved beam quality and may improve loss conditions in the Linac enclosure. Residual activation of Linac at operating intensity for Proton Plan 2 operation will not pose a limitation on Proton Plan 2.

2.4.3.2 BOOSTER

Ground water activation at the Booster was extensively reviewed during the 1998 Shielding Assessment and was a consideration (but not a limitation) in establishing the Beam Permit. A ground water activation safety factor of 3.4 was determined in the 1998 assessment based upon historical operation and beam loss patterns in the Booster. Improvements in beam loss control in the Booster should lead to significant decreases in the ground water source terms determined in that assessment. Ground water activation at the Booster accelerator should not pose a limitation for Proton Plan 2 operation at 700 KW.

Surface water is routinely monitored at sump discharges associated with the Booster. Typical tritium levels found average a few picocuries per milliliter or less. In 2006, the Booster sump discharges were redirected to controlled retention ponds and continue to be routinely monitored and managed. Booster operation to support Proton Plan 2 will not pose an environmental concern.

Air activation had been continuously monitored at major beam loss points in the Booster by AD ES&H Department. No significant losses were detected in these monitoring programs. Historically, the presence of low levels of activated air was noted at exit stairwells around the Booster. Beam loss control initiatives (discussed below) undertaken by the Booster Department in recent years has significantly reduced or eliminated low levels of activated air due to improved control of beam loss. Air activation due to Booster operations will not pose a limitation on Proton Plan 2 operation.

Residual activation in the Booster has been given a great deal of attention in recent years. This has been driven by the need for Booster to provide record intensity to a number of users--most notably the Antiproton Source, MiniBoone, and NUMI. Some initiatives undertaken to reduce beam loss in the Booster include:

- Removal of long 13 extraction
- Installation of collimation systems
- Active monitoring and control of Booster losses through the beam loss monitoring system
- Alignment of Booster components to improve aperture
- Measurement and tracking of residual radiation levels in the Booster by Booster Department personnel along with determination and implementation of corrective action
- Reduction of orbit distortion through dogleg magnets

- Improved beam extraction systems

As mentioned earlier, the Linac quadrupole power supply regulation upgrade promises to deliver improved quality beam from the Linac which should also help to further reduce activation levels in the Booster. Residual activation in the Booster should not pose a limitation on the Proton Plan 2 upgrades. Beam loss management in the Booster will continue to be required.

2.4.3.3 MI 8 Line

Groundwater was extensively reviewed for the MI project. Residual activation routinely found in the MI8 line is historically quite low. Ground water activation does not pose a limitation on Proton Plan 2 operation.

Surface Water is routinely monitored in MI 8 Line sumps. Periodic sump sample results from MI8 line routinely show less than detectable radioactivity. Surface water resulting from operation of the MI 8 Line does not pose a limitation on Proton Plan 2 operation

MI8 Line air activation in the MI8 Line has been monitored by the AD ES&H department. No significant activity has been detected. Air activation in the MI8 Line should not pose a limitation on Proton Plan 2 operation.

Residual activity in the MI 8 Line has historically been quite low, residual activity levels in the MI 8 line (except at Booster extraction and MI injection) are quite low

Residual activation due to MI 8 line operation does not pose a limitation on Proton Plan 2 operation.

A new beam collimation system has been designed and built for the MI8 line [47]. Radiological concerns for the collimation system have been addressed. Operation of the new collimation system in the MI 8 Line will not pose a limitation on Proton Plan 2 operations.

2.4.3.4 MAIN INJECTOR and Recycler Ring

Ground water was extensively reviewed during the Main Injector shielding assessment. Ground water activation does not pose a limitation on Proton Plan 2

Surface water is routinely monitored at 17 sump locations around the Main Injector. Tritium levels found in the sump water are typically less than the detection limit of 1 pCi/ml. Recently, a small number of samples have been found with 1 to 3 pCi/ml. Beginning in 2005, Main Injector sump discharges are being directed to controlled retention ponds and routinely monitored and managed. Main Injector surface water activation does not pose a limitation on Proton Plan 2 operation.

Air activation has been monitored in the Main Injector by the AD ES&H Department. Beam losses are distributed around the Main Injector and no significant sources of air activation have been identified. Control of beam losses in the Recycler Ring and the Main Injector, as discussed below, is the primary method available to control air activation. Air activation due to operation of the Recycler Ring and the Main Injector should not pose a limitation on Proton Plan 2 operation.

Residual activation in the Main Injector is actively managed by Main Injector Department personnel. Loss points are determined in radiation surveys by department personnel. Orbit corrections or optics corrections are applied. Follow up radiation surveys are made and improvements in Main Injector residual activation levels have lead to dramatic reductions in residual activation in spite of increasing Main Injector beam power.

2.4.4 References

36. Cossairt Criteria
37. Antiproton Source Shielding Assessment, 2000
38. Shielding Requirement Calculator, Excel Spreadsheet
39. 1998 Booster Shielding Assessment
40. Radiation Protection Utilizing Electronic Berms, John Anderson Jr. and Glenn Federwitz, "High Intensity And High Brightness Hadron Beams": 20th ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams ICFA-HB2002, AIP Conference Proceedings, Dec. 2, 2002, Vol. 642, pp. 125-129
41. Private conversation with John Anderson, 10/06
42. Plan for Recycler Ring eberm operation, A. Leveling, 10/06 (draft pending)
43. Main Injector Shielding Assessment 1998
44. MI Shielding Verification, A. Leveling 1999
45. Main Injector Shielding Assessment, October 2004
46. Fermilab Radiological Control Manual
47. MI8 Beamline Collimation Design, B.C. Brown, 9/30/2005

2.5 NuMI upgrades (WBS 1.4)

2.5.1 Introduction

Plans for the future operation of the NuMI beamline under Proton Plan 2 include neutrino production for the NOνA and MINERνA experiments at a primary beam power up to 700 kW. For the NuMI beamline this implies a modest increase of the protons per pulse on the target and a decrease in the cycle time to 1.33 seconds as summarized in Table 14.

	Best Operations	**NuMI Design**	**Proton Plan 2**
Beam power to NuMI (kW)	**290**	**400**	**700**
MI intensity (ppp)	**3×10^{13}**	**4.0×10^{13}**	**4.9×10^{13}**
MI cycle time (seconds)	**2**	**1.9**	**1.33**
Spot size on target (mm RMS)	**1.0**	**1.0-1.2**	**1.3**
Protons/hr	**5.6×10^{16}**	**7.3×10^{16}**	**13×10^{16}**

Table 14: Summary of beam parameters for the NuMI upgrade. The best operation was achieved in November 2006 during a period without pbar stacking.

The essential nature of the neutrino production process (see [48] for instance) is unchanged for Proton Plan 2. The first step in the production of the NuMI neutrino beam is directing a beam of protons from Fermilab's Main Injector onto a production target. Interactions of the proton beam in the target produce mesons (mainly pions and kaons), which are focused toward the beam axis by two magnetic horns. The mesons then decay into muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining protons and mesons from the beam. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through it to an experimental hall at Fermilab and onwards toward "far" detectors. A picture of the NuMI tunnel is shown in Figure 30 and a schematic of the neutrino production process is shown in Figure 31. More detail of the NuMI beamline can be found in the NuMI Technical Design Handbook [49].

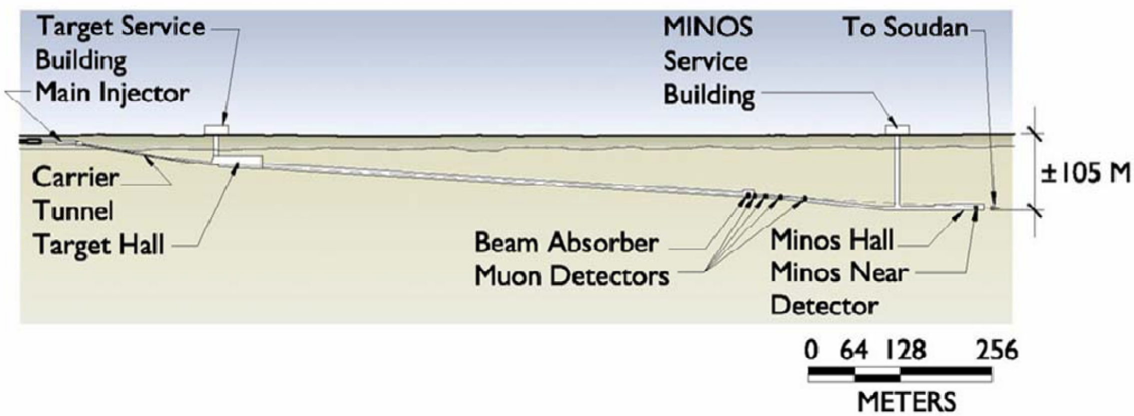


Figure 30: The NuMI beamline tunnel. Protons are delivered from the Main Injector via the primary beamline located in the carrier tunnel. The target and focusing horns are located in the target hall. The long section in the middle contains the decay pipe which is followed by the beam absorber, muon detectors, and experimental hall.

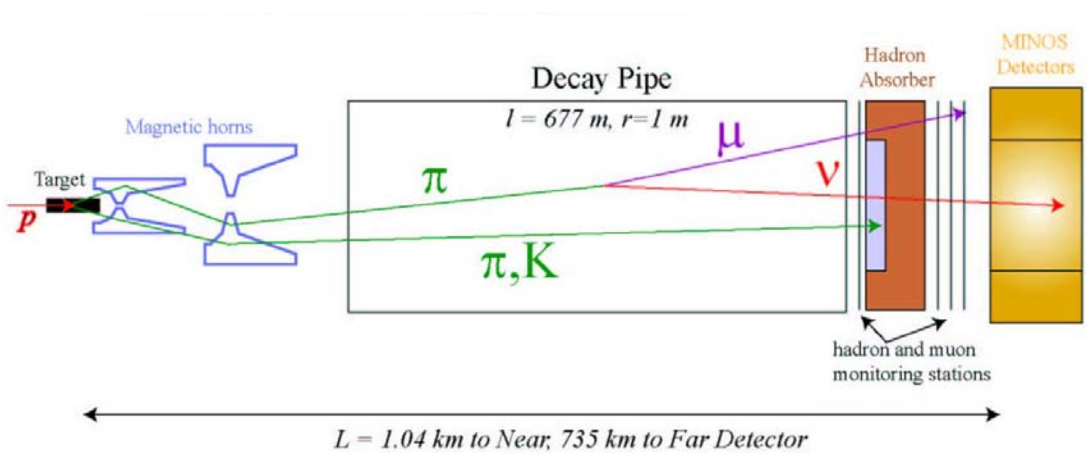


Figure 31: A schematic of the neutrino production process in the NuMI beamline. Pions and kaons are produced by protons hitting a graphite target and then focused with magnetic horns. The pions

and kaons then travel down a long decay pipe giving them time to decay into muons and neutrinos. The remaining hadrons are stopped by the hadron absorber and rock between the end of the decay pipe and the experimental hall containing the near detector.

For the focusing of the pions NuMI has chosen magnetic horns with parabolic shaped inner conductors. These produce magnetic fields that act to first order as lenses, where the focal length is proportional to the pion momentum. Thus a selection of a particular target position causes a certain momentum to be focused by the first horn. Pions that were well focused by the first horn pass unaffected through a central aperture in the second horn. Pions that were somewhat over- or under-focused by the first horn move to larger radius and are focused by the second horn, extending the momentum bite of the system. To fully optimize a neutrino beam energy configuration it is necessary to optimize the locations of both the target and the second horn. Three different target and second horn positions have been chosen for low, medium and high energy neutrino beams, resulting in the spectra shown in Figure 32.

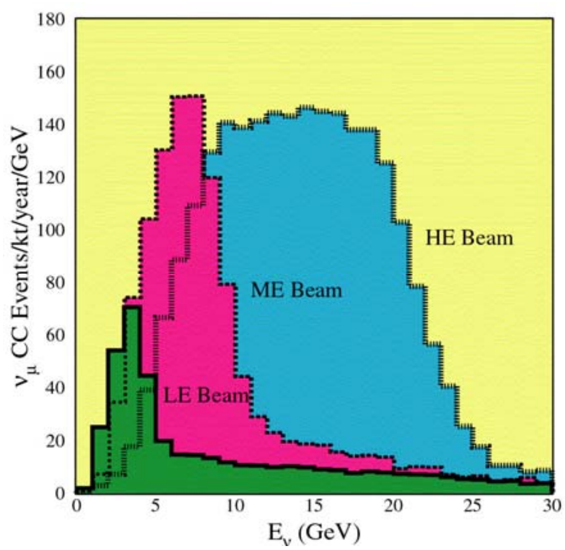


Figure 32: Expected spectra of charged-current (CC) events at the MINOS far detector for low (LE), medium (ME) and high (HE) energy beam configurations.

2.5.1.1 Neutrino Experiments

In present operations NuMI provides neutrinos for the MINOS (Main Injector Neutrino Oscillation Search) experiment [52], which consists of two massive detectors. The "near" detector is located at Fermilab in the experiment hall at the end of the NuMI beamline tunnel and the "far" detector is located in the path of the neutrino beam 735 km away in Soudan, Minnesota. The MINOS experiment is optimized to explore the region of atmospheric neutrino oscillation parameter space. Thus MINOS operates with the NuMI beamline in the low energy configuration which produces neutrinos mostly in the ~1-5 GeV energy range. This experiment has recently reported observations of muon neutrino disappearance [53].

Planned for the future are two other neutrino experiments: the MINERνA (Main INjector ExpeRiment for ν-A) experiment [54] and the NOνA (Neutrino Off-axis ν_e Appearance) experiment) [55]. The MINERνA detector will be located in the NuMI experimental hall just upstream of the MINOS near detector. The main purpose of this experiment is to improve the knowledge of neutrino-nucleus interactions. A fraction of the data, corresponding to about 4E20 protons on target**,** will be collected with NuMI in the low energy target configuration just like the MINOS operations. Intensity limitations of the present low energy target and horn design prevent increases of the beam power much beyond the 400 kW design value. (MINERνA would like to get a total of at least 16E20 POT including operations with the higher energy neutrino spectrum.)

As in MINOS, the NOνA experiment has both a near and a far detector except that the detectors are located off of the neutrino beam axis. Locating the detectors off axis narrows the spread of neutrino energies hitting the detector, which is an advantage for electron neutrino appearance measurement proposed by NOνA. The physics potential is optimized if the NuMI beamline is run in the medium energy configuration with the far detector located approximately 810 km away from Fermilab and 12 km off of the neutrino beam axis. The medium energy configuration provides a neutrino beam with energies mostly in the ~3-10 GeV range on axis, but with neutrino energies mostly in the ~1-3 GeV energy range at the off axis location of the NOνA detector. Changing to the medium energy configuration allows the NuMI beamline to operate with a different target design which is capable of handling higher beam power.

2.5.1.2 Scope of the upgrades

While most of the effort for Proton Plan 2 is related to the higher beam power, the target and focusing horn configuration (optics) is also changed to meet the needs of the future experiments. This means moving the target and the second horn to new locations within the target chase area in order to change the energy spectrum of the neutrinos. A description of the different configurations is given in [49].

The 75% increase in power, from 400 kW to 700 kW, resulting from Proton Plan 2 involves:

- Reducing cycle time from 1.87 sec to 1.33 sec (40% increase in power)
- Increasing the per pulse intensity from 4.0E13 to 4.9E13 (22% increase in power)

In the following sections conceptual designs are presented for each of the NuMI beamline systems requiring upgrades for Proton Plan 2. Here we summarize the scope of the upgrade by listing the major changes needed:

- Replace five of the primary beamline quadrupole magnets. The new magnets are designed to handle the higher heat load of a faster cycle time.
- Replace the existing target and baffle with a new design capable of handling the higher beam power.
- Modify the design of focusing horns to maintain stress limits under the increased heat load. Replace the existing horns with the modified design.
- Reconfigure the target chase from the low energy neutrino configuration to the medium energy neutrino configuration. Mostly this means repositioning horn 2 and extending the horn stripline.

- Add capacity to the target chase cooling system to maintain a reasonable temperature of the target pile.
- Upgrade the capacity of the cooling water systems including the RAW systems for the target, horns, decay pipe, and hadron absorber.
- Update the beam permit system to prevent accident conditions which can damage beamline components.
- Upgrade the work cell used to provide radiation shielding while repairing targets and horns.

The implementation of the upgrades is planned to occur during two separate shutdown periods. The first shutdown period follows the completion of Collier Run II operations at the end of FY 2009. During this shutdown the NuMI beamline begins preparation for the 700 kW operations and accomplishes the following tasks:

- Upgrade the target chase cooling system
- Upgrade the capacity of the RAW systems
- Replace the quadrupole magnets in the primary beamline
- Extend the horn 2 stripline
- Modify the target chase shielding in preparation for the future horn 2 relocation.
- Modify the work cell.

It is estimated that accomplishing these tasks will take 4-5 months.

After the first shutdown the MINERνA experiment will operate for about 1 year in the low energy configuration. Since this requires the use of the existing target, the NuMI beamline will be capable of only ~400 kW of beam power. Upon completion of the MINERνA operations in the low energy configuration a second shutdown is planned to switch from the low energy configuration to the medium energy configuration. Since this involves replacing the low energy target with the medium energy target, NuMI will be capable of operating at 700 kW (Proton Plan 2) following the second shutdown. The second shutdown involves the following tasks:

- Replace the target with the medium energy target
- Replace the horn 1 with the new design
- Relocate horn 2
- Replace the horn 1 module with a new design (if needed.)

The length of the second shutdown is estimated to be between 6 to 10 weeks. The length of the shutdown depends on the necessity of replacing the horn 1 module. Without the horn 1 module replacement, the shutdown work can be finished in about 6 weeks. With the horn 1 module replacement the shutdown will take about 10 weeks.

2.5.2 Primary Beamline

The current 400 kW design NuMI beam has the capability to extract up to 6 Booster batches from the Main Injector at a cycle time of 1.87 sec. Both the extraction system and primary beam transport are of conservative design, with robust operation for NuMI demonstrated and operational beam loss levels consistently 1-2 orders of magnitude below the relatively severe NuMI design criteria of 1×10^{-5} fractional beam loss. If the next level upgrades for beam intensity capability, involving slip-stacking of multiple batches to NuMI, can maintain the level of beam control achieved for NuMI, a significant window for higher per pulse beam intensity is available. The most significant modification of the NuMI primary beamline for Proton Plan 2 involves acquiring the capability for faster cycle repetition rates. More detail can be found in [56].

2.5.2.1 Extraction Kickers

A modest upgrade is required for the NuMI extraction kicker system which, due to unchanged primary energy, will still operate at 50 kV. The shorter cycle time reduces the available time for power supply charging from 1.1 to 0.7 sec. This leads to the requirement for a new charging power supply.

An upgraded fluorinert pump is also required for the existing water heat exchanger to handle the additional heat load caused by the increased repetition rate.

2.5.2.2 QQM 3Q120 Quadrupole Magnets (WBS 1.4.1.3)

The most significant upgrade expenditure to acquire Proton Plan 2 capability for the NuMI primary beam is with the 3Q120 quadrupole magnets. For NuMI these magnets were refurbished from existing fixed target beam system inventories, as were the large NuMI dipoles. The dipole refurbishment effort was straightforward, but with the quads a number of magnets were found with internal cooling leaks during this process. The available laboratory supply of 3Q120 magnets was exhausted to successfully refurbish the 19 ones needed for NuMI, along with two spares.

For these 25 to 30 year old magnets a concern is that the water-cooling of the coil packs is very inefficient since there is no direct cooling for the coils themselves. To provide some safety margin, cooling for the highest current NuMI quadrupoles was augmented with external cooling plates as shown in Figure 33 below.

Figure 33: NuMI 3Q120 with External Cooling Plates

There have been no failures of installed NuMI quadrupoles to date, but a strong recommendation from the Technical Division (D. Harding) is that for cycle times below 1.87 seconds we should replace the highest current NuMI quads (those operating at greater than 70 amps) with newer design QQB magnets having direct water cooled coils.

Hence, the Proton Plan 2 requirement here is:

- Building 6 new QQB design 3Q120 magnets to replace the 5 highest current NuMI QQM design magnets, plus one spare.
- The five quads and their currents are
  - Q111 (78 A)   Q112 (83A)   Q113 (83A)
  - Q114 (78A)   Q120 (71A)
- QQB design has internal coil cooling, fewer turns and higher current for same field.
- Projected to be **much** more robust.

Specification differences between QQM and QQB quadrupole magnets are shown in Table 15.

	QQM	QQB	Units
Turns per pole	118	28	
Resistance	1.6	0.16	Ohm
Inductance @ 100 Hz	1.4	0.082	H
Water flow @ 100 psi (not including supplemental plates)	17	5.7	GPM
Core width	17	17	Inches
Core height	15	15	Inches
Steel length	120	120	Inches
Flange-to-flange length	132.0	132.0	Inches
Core to lead end flange	5.0	6.5	Inches
Core to bellows end flange	7.0	5.5	Inches
Assembly drawing	ME-388120 Link to TIF	ME-331805 Link to TIF	

Table 15: QQM quadrupole magnet versus QQB quadrupole magnet specifications.

2.5.2.3 Large Power Supply Modifications (WBS 1.4.1.2)

Relatively minor changes are needed to existing large dipole power supply setup to enable the faster cycle time for Proton Plan 2. These are summarized in Table 16 below.

I:LAM6 0	**Tap change** from 50 to 100 volts. RMS current from 474 A to 434A
I:LAM61	**No change.** Increase RMS current from 931A to 1073A
E:V100	**Tap change** from 50 to 100 volts. RMS current from 1426A to 1226A
E:HV101	**No change.** Increase RMS current from 814A to 932A
E:V118	**Use full voltage.** Increase RMS current from 2270A to 2292 A

Table 16: Large power supply changes for 1.33 second cycle time.

2.5.2.4 Improved PS Readout Capability

Currently the Beam Permit System monitors the large power supply currents only to ~0.5 to 1.0 %. This provides a significant window where a power supply flat top drift within this range could lead to mis-steered beam and create a single pulse with large beam loss. To preclude this robustly, we need to monitor the power supply current to ~0.01% as input for the beam permit system.

The recommended solution is to implement "bulb" regulation systems in the 6 major power supplies. (A system is currently installed on HV101, but not yet fully tested). This naturally provides the precision readout capability, as well as improved power supply regulation.

2.5.3 Target Hall

A layout of the NuMI hall with the main components is shown in Figure 34 and Figure 35. The components included in the target hall are:

- Radiation shielding
- Baffle
- Target
- Target/baffle carrier which moves the target longitudinally to change neutrino beam energy
- Beam focusing horns, including field monitoring probes and a cross hair system to check the horn alignment with beam
- Modules that have the target carrier and horns attached. These allow remote installations and provide radiation shielding.
- A Work Cell where broken radioactive components hanging from the modules can be replaced
- Air cooling system for target pile
- Remote stripline connection for horns
- Instrumentation
- A morgue for storing used radioactive components
- Power supplies and RAW systems (located outside the target hall)

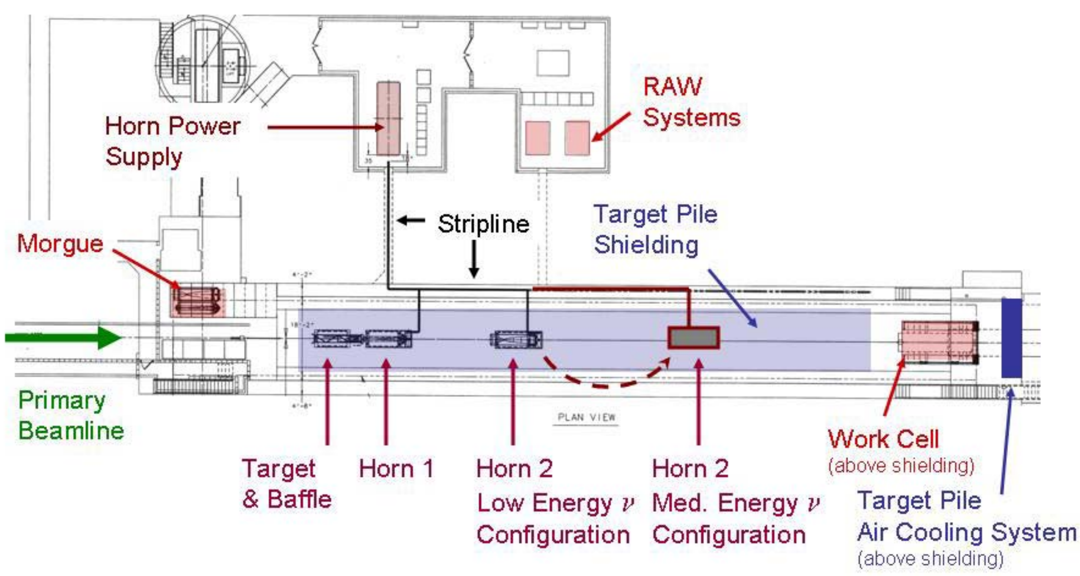


Figure 34: Plan view of the NuMI Target Hall. Note that the Horn 2 location depends on the neutrino energy configuration.

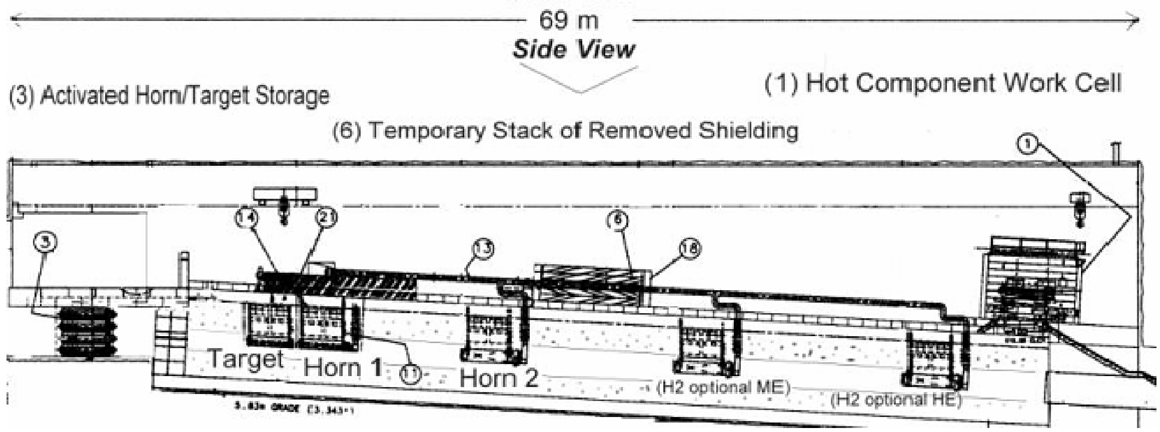


Figure 35: Elevation view of the NuMI target hall. Note the three possible locations for Horn 2 corresponding to the Low, Medium, and High Energy neutrino spectrums shown in Figure 32.

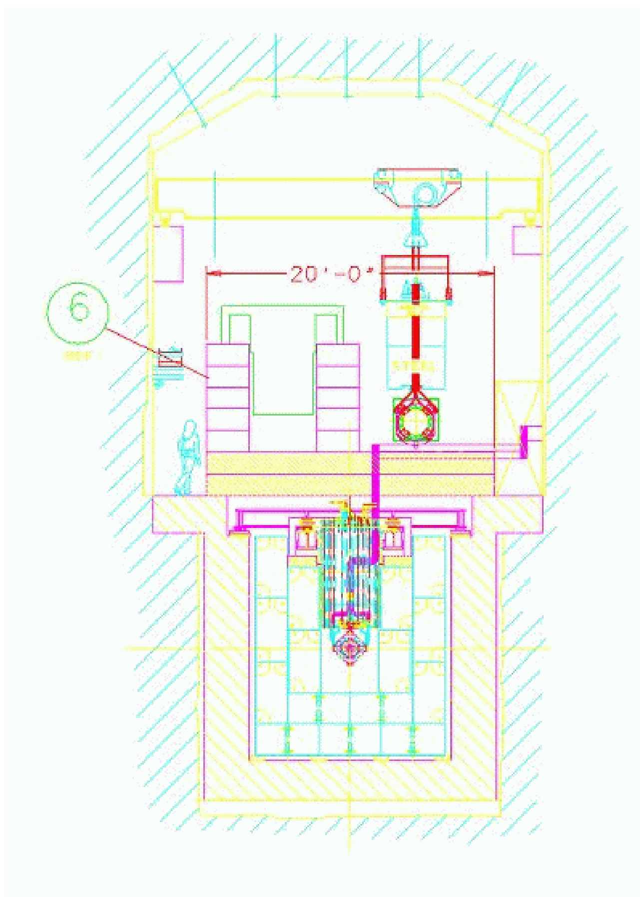


Figure 36: Cross sectional view of the NuMI target hall, showing a temporary stackup of removed shielding, and a module plus horn being transported.

2.5.3.1 Target Hall Neutrino Energy Configuration

Presently the NuMI beamline operates in the low energy configuration for the MINOS experiment and produces neutrinos mostly in the range from 1 to 5 GeV. In this configuration the target extends 50.4 centimeters into the first horn as shown in Figure 37. This restricts the outer diameter of the target casing to a maximum of 30 mm and places constraints on the design of the target graphite and water cooling. As a result, the target cannot handle much beyond 400 kW of beam power. The target is described in more detail in Section 2.5.4.2. In the low energy configuration Horn 1 and Horn 2 are spaced 10 meters apart as shown in Figure 35 and both horns are pulsed to 200 kA with a 2.3 ms long half sine wave.

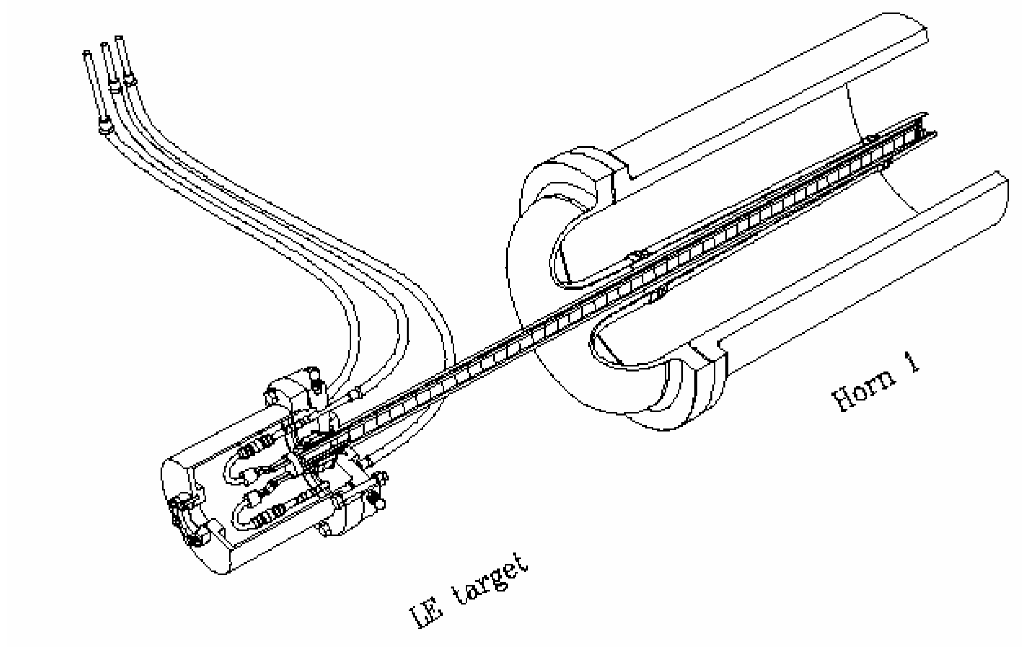


Figure 37: Picture of the low energy target inserted into the first horn.

In the medium energy configuration planned for NOvA Horn 1 does not change location, but the target is moved further upstream and the Horn 2 is moved 13 meters further downstream. This configuration produces neutrinos mostly in the 3 to 10 GeV range on the beamline axis, but 14 mrad off axis, at the location of the NOvA far detector, the neutrino energies are mostly in the 1 to 2.5 GeV range. The target position is moved far enough upstream that it does need to fit within Horn 1. This removes dimensional constraints on the target and allows for a target design capable of higher beam power. The target is described in more detail in Section 2.5.4.2. As in the low energy configuration both horns are pulsed to 200 kA with a 2.3 ms long half sine wave.

2.5.4 Baffle and Target

2.5.4.1 Target Baffle

In the NuMI baseline design a 1.5 m long baffle 68 cm upstream of the target fin protects the neck of the horn and the target cooling hardware from mis-steered beam pulses. The baffle moves along with the target from Low Energy (LE) to High Energy (HE) locations.

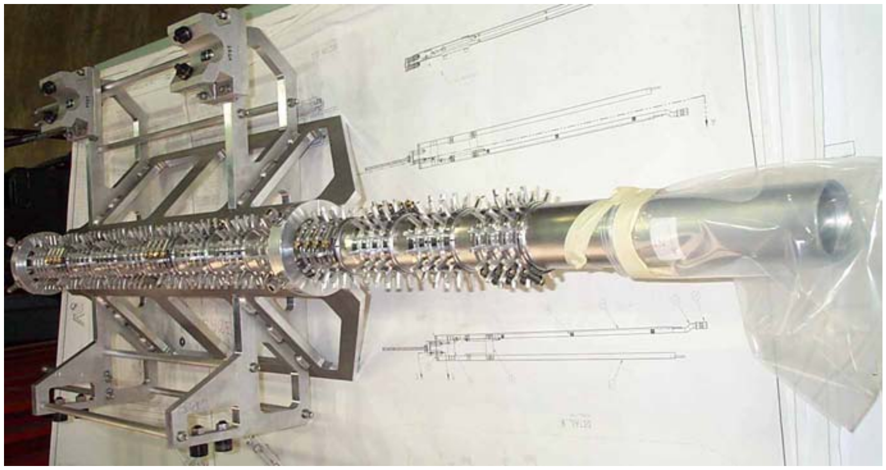


Figure 38: NuMI target pile baffle

The upgrade beam intensity of 4.9E13 protons/spill is 22% higher than the NuMI baseline design. In the base design, excluding high-cycle fatigue (which the baffle should not be subject to) the stress safety factor of the baffle in accident conditions is 4.5 [62]. So the baffle design is well inside the safety factor and the baffle will survive the shock of accident conditions in Proton Plan 2 running.

The baffle serves to protect the horn neck and the target cooling system. The heating (and thus induced stress) of various components is shown in [50] as a function of the baffle location; moving the baffle upstream reduces the stress. For Proton Plan 2, the move of the target to the ME location naturally moves the baffle further from the horn neck, compensating for the higher intensity per spill. The protection of components of the new target will have to be evaluated, but based on the safety factors for the old components is likely to be OK without modification of the baffle. If desirable, the baffle can be moved another 1 m upstream of the target (to its current location for the HE beam), increasing the stress safety factor.

The D.C. beam power in the upgrade is 75% higher than the NuMI baseline design. The baffle is air-cooled with pin radiators, and the temperature rise is used to monitor the amount of beam scraping. Calibration with real beam shows the original safety factor would cover the increased temperature but there is room for more pin radiators on the baffle which should be added.

Although SLG grade R7650 graphite was used in the baffle rather than the POCO ZXF-5Q used in calculations in [50], R7650 actually has a slightly better combination of yield strength, heat capacity, coefficient of thermal expansion and Young's modulus.

2.5.4.2 Target

The low energy target is described in chapter 4 of the NuMI Technical Design Handbook [49] and in several reports from IHEP [57, 61]. The target material is graphite, type ZXF-5Q (POCO Graphite), with a density of 1.78 g/cm^3. The main target consists of 47 vertical target segments 20.0 mm long and 6.4 mm wide. With 0.3 mm of spacing between the segments the total length of the graphite section is 95.38 cm. Figure 39 shows a picture of the target and the target canister. Vertically the graphite segments are between 15 and 18 mm tall and sculpted to fit snuggly against a water-cooling pipe on both the top and bottom. A cross section of the target segment is shown in Figure 40.

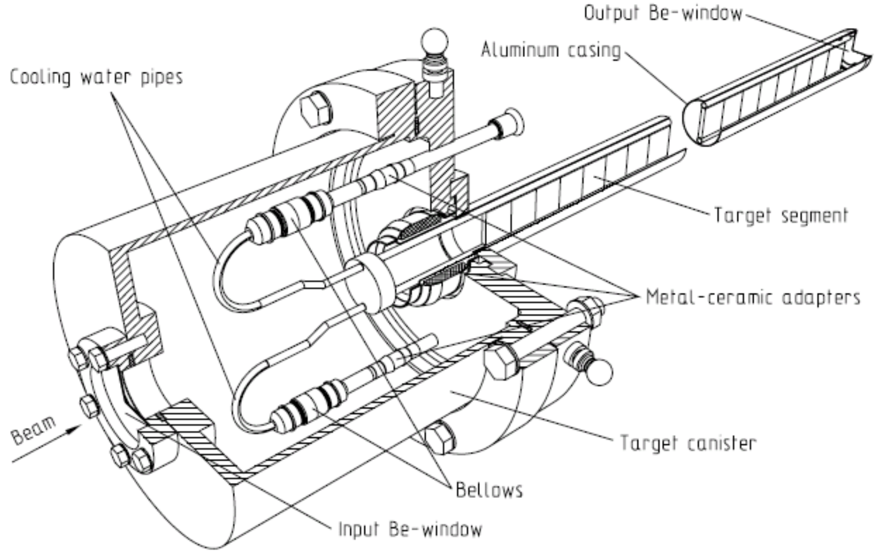


Figure 39: The low energy target and target vacuum canister.

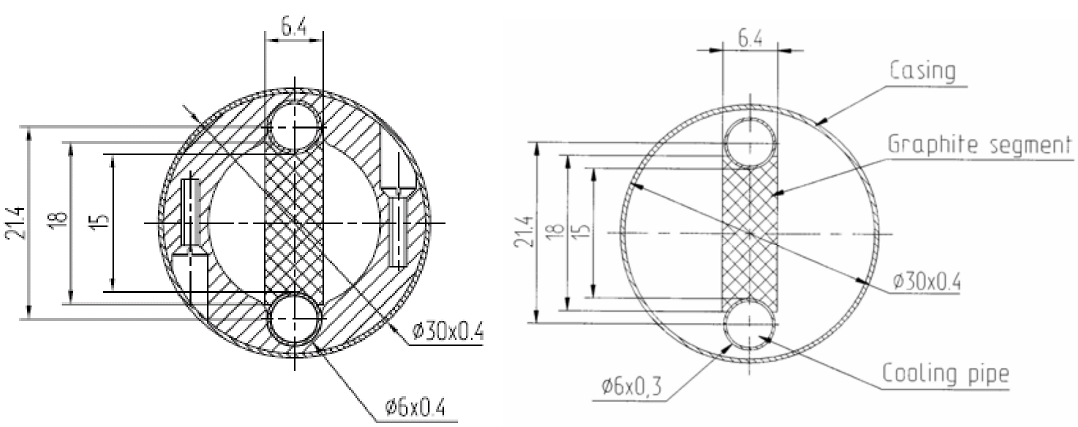


Figure 40: Cross section of the low energy target. The dimensions are in mm.

During present operations the spot size of the beam at the target is roughly a round Gaussian with an rms width of 1 mm but this varies somewhat from day to day. Typically the target profile monitor upstream of the target measures rms beam widths of the beam in the 0.9 mm to 1.2 mm range depending on the beam intensity and performance of the upstream machines [68].

In future MINOS and MINERνA operations (but before Proton Plan 2 operations) the intensity of protons on target is expected to increase to as much as 4.5E13 per pulse with the implementation of multi-batch slip stacking in the Main Injector. A recent report from IHEP (Protvino) [69, 70] has computed the stresses and temperature of the low energy target with 5.5E13 protons per pulse every 2.2 seconds (which corresponds to 480 kW of beam power). The report concludes that target is able to withstand this beam power if the proton beam spot size is increased to at least 1.3 mm rms.

However, the instantaneous temperature rise in the cooling water reaches a maximum of about 4.6 °C at the downstream end of the target. This leads to a 30-atmosphere adiabatic pressure rise in the cooling lines. In the case of the 9 μs beam pulse this may give rise to the failure of the cooling system due to the hydraulic shock. Further analysis needs to be performed to determine if this is a problem, but one solution might be to remove the bellows from the design. Another possible solution is a bubbler system which injects small bubbles into the RAW system. The bubbles act as shock absorbers to reduce the stress from the rapid water expansion. This idea requires analysis to determine its effectiveness.

2.5.4.3 Medium Energy Target

Proton Plan 2 assumes a medium energy neutrino configuration required by the NOνA experiment as discussed in Section 2.5.3.1. In this configuration the optimal location for the target begins 135 cm upstream of Horn 1 and extends to 15 cm upstream of Horn 1. The IHEP group has designed an optimized target for this configuration. The medium energy target design is nominally the one described in IHEP reports [73, 74], except that the graphite fin width is 6.4 mm instead of the original 3.2 mm.

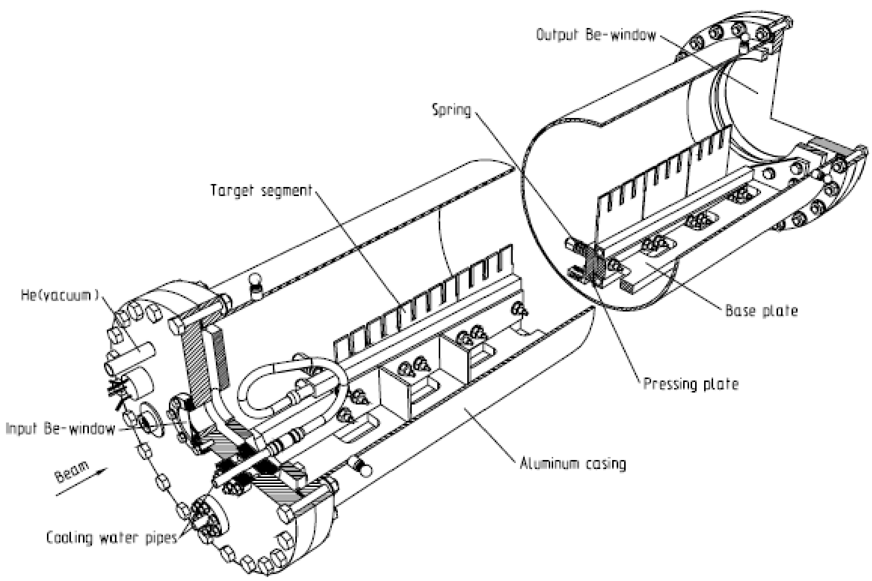


Figure 41: View of the medium energy target.

A view of the ME target design is shown in Figure 41. The incident protons travel through the upper portion of twelve 6.4 mm thick and 100 mm long graphite plates. The bottom of the graphite fins is clamped by a base plate that contains water-cooling channels. Two springs per target plate provide ~2 atmospheres of pressure. The distance from the fin tip to the cooling channel is minimized at the upstream end where beam heating is maximal. To prevent absorption of secondaries contributing to the neutrino flux, the fin extension increases continuously along the target length. The base and pressing plates are made of an aluminum alloy and anodized with 30 μm thick alumina. To decrease quasi-static thermal stresses cuts are machined in the upper part of each graphite plate forming four 22 mm long, 30 mm high segments (or teeth).

Note that the casing diameter for the medium energy target is wider than the inner conductor of Horn 1 and therefore operations in the low energy configuration are precluded with this target design.

The longitudinal position of the ME target will remain fixed and will not be remotely moveable. Remote motion capability in the transverse plane will still be provided in order to perform target and horn scans. In order to perform horn scans the design of the target carrier and motion apparatus must provide enough travel to completely remove the target and aluminum casing from beam path.

IHEP has performed preliminary calculations of stress and temperature in the ME target as a function of beam spot size from 1.0 to 1.5 mm rms for up to 5.5E13 protons per pulse every 1.3 seconds corresponding to a primary beam power of 780 kW. The preliminary results show that the target design is capable of withstanding the beam power [58].

2.5.5 Horn System

The NuMI horns are pulsed toroidal electro-magnets that focus pions generated in the target. The pions then decay to produce the neutrino beam.

The focusing properties of the horn system should remain unchanged for Proton Plan 2. The horn system design changes are driven by the increased pulse repetition rate and increased beam heating. The horn system was designed to run 205 kA half-sign-wave current pulses of width 5.2 ms every 1.87 seconds. The system is currently running 185 kA to 200 kA pulses of width 2.3 ms every 2 to 3 seconds. For Proton Plan 2, we expect to run 200 kA pulses of width 2.3 ms every 1.33 seconds.

Because of the reduced pulse width compared to design, joule heating of the horns, stripline, and power supply components will still be less than the original design, even with the increased repetition rate.

2.5.5.1 Horn Design

The Horn 1 inner conductor is only 2 mm thick, and is water-spray cooled. Its heat load is dominated by joule heating. The temperature limitation is essentially that the surface be less than the boiling point of water. No modification to the inner conductor should be needed for Proton Plan 2.

The Horn 1 outer conductor is currently 25.4 mm thick. Its heat load is dominated by beam heating. Spray nozzles are directed inside at the top of the cylinder, and water runs down the sides. Alignment tolerances dictate that the temperature does not vary more than 10 °C from top to bottom. There is not much safety factor on this cooling in the NuMI design so some modification is required for Proton Plan 2. Rather than try to increase the uniformity of the water-cooling, the idea is to reduce the heat load by reducing the thickness of the outer conductor to between 13 to 16 mm.

2.5.5.1.1 Horn Module and Hanger

The residual radiation levels of the NuMI horn and target chase pile make remote installation and removal to the NuMI horn a necessity. This is accomplished by supporting the horn below a horn module. The entire horn and module assembly, as shown in Figure 42, can then be moved remotely by crane between the target chase and work cell. Once in the work cell the horn can be connected (or disconnected) from the module by remotely latching (or releasing) the horn hanger from the top of the horn module. The horn and horn module design also includes remote connection of the water-cooling lines and striplines.

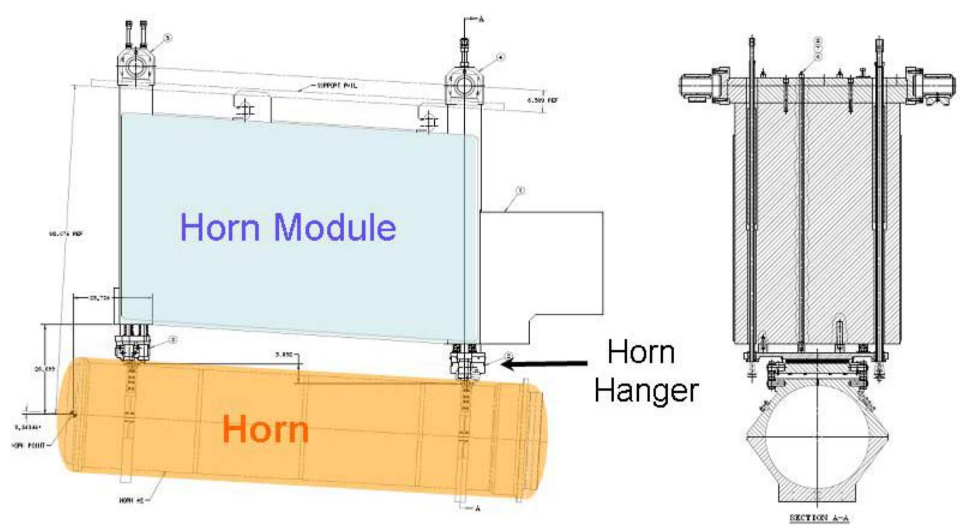


Figure 42: Side and front view showing the NuMI horn hanging below the horn module. The horn is attached to the horn module by locking the horn hanger remotely from the top of the horn module.

Issues that may require horn module modifications for the NuMI upgrade running include the following:

- Increased beam heating could affect material properties
- Increased beam heating could affect alignment via thermal expansion

- Utilities to the components could require extra penetrations through the module
- Corrosion could motivate replacement of parts of the module, perhaps with more corrosion resistant materials.

The Horn 1 module is the only one of the three modules with significant beam heating. Initial thermal modeling of the horn 1 module yields a maximum temperature of 105 °C at the bottom of the module for 700 kW beam operation (Proton Plan 2). This is low enough that all of the materials used there will be OK.

Based on the thermal modeling, Finite Element Analyses were run to estimate the resulting motion of horn 1 due to thermal expansion [59, 60]. The resulting vertical horn motion is 0.8 mm, and horizontal motion is 0.4 mm. Putting in an ad-hoc asymmetric heating of the module increased the horizontal motion to 0.7 mm. These offsets are within the alignment tolerance of 1.5 mm specified by the NOVA experiment.

The extra utilities needed at the components for Proton Plan 2 are (i) cooling to the strip-line for Horn 1 and (ii) extra channels of temperature monitoring at Horn 1. At this point, the routing for cooling to the horn strip-line is assumed to be through either the strip-line block or through a specially designed T-block, and not affect the module. There are enough spare instrumentation connector slots to allow increased temperature monitoring for the horn 1 module (only 11 of the 20 slots are currently used). For the target module, all instrumentation slots are currently used, but the module hole for longitudinal target drive (for moving target along beam direction) will no longer be needed, and could be used to supply five extra instrumentation slots if needed. Thus no modifications to the modules for utilities are envisioned at this time. This assumes that the modification of thinning the horn outer conductor is carried out, so that no extra cooling water to the horn is needed for the higher beam power.

Vertical and transverse-horizontal motion of Horn 1 and target is accomplished by moving shafts that are routed through the module end-walls. This is particularly critical for the target, since large vertical motion is desired to move the target out of the way to allow for beam-scans of the horn system for alignment checks. The target shafts are already significantly corroded, and will need to be replaced with corrosion-resistant shafts for Proton Plan 2 operation. The original module design includes features to allow replacement of the shafts without building an entire module, but it is not a trivial task.

2.5.5.1.2 Horn Power Supply

To operate the horns at the faster 1.33 second cycle time requires a faster charging time for the horn power supplies. Presently the capacitor bank is charged in 1.2 seconds (nominally) just prior to discharge and the PEI charging current runs about 140 Amps dc. At the current rep-rate of 2 seconds, the resultant rms current is 5100 Amps in the capacitor bank, stripline, and horns.

The PEI can run as high at 300 Amps dc and the supply and striplines were built to run at an rms current of 7,400 Amps when running at 200 kA (peak) and 1.9-second rep-rate. Thus the horn power supply can charge fast enough, with room to spare, at 1.3-second rep-rates and will still not exceed any power dissipation limits in the PEI, the capacitor bank, or the striplines.

2.5.5.1.3 Horn cooling

The water-cooling of Horn 1 while operating the beamline at 700 kW will be an issue for Proton Plan 2. The horn is cooled by spraying water into the interior of the horn between the inner and outer conductor. The nozzles spraying water are designed to form a film along the inside surface of the outer conductor to provide cooling. Simply increasing the flow rate is not a possibility because the higher flow rates will disrupt the smooth flow of water along the surface and interrupt the water-cooling.

In its initial design the outer conductor of Horn 1 is 1 inch thick. This provides a significant amount of material for energy deposition and at 400 kW of beam power there are 14 kW of beam energy deposited in the outer conductor. A conservative design of Horn 1 led to the choice of a 1-inch thick outer conductor and for Proton Plan 2 this will be changed to a 5/8-inch thick outer conductor. The reduction in mass of material will also reduce the amount of beam energy deposited in the outer conductor and compensate for the increased beam power.

A complete analysis of the Horn 1 design is needed to be sure that the stress levels are acceptable and that the water-cooling will be sufficient.

2.5.6 Horn 2 Relocation

To switch from the low energy to the medium energy neutrino spectrum Horn 2 will need to be relocated approximately 13m further downstream from its current position in the target chase. This will require significant reconfiguration of the existing shielding layout. A longitudinal cross section of the target hall shielding is shown in Figure 43 together with the proposed new Horn 2 location. Concrete “R” blocks placed on top of the target vault (to seal the target pile and provide shielding) are also used for shielding and storage of the T-blocks and blue blocks as shown. Since the new horn location falls beneath the existing T-block and blue block storage space, a completely new shielding storage scheme will have to be developed. A detailed study of the available space will be conducted aimed to develop a comprehensive new layout plan for the various target hall activities, such as target and horn change outs, repairs, and work cell activities.

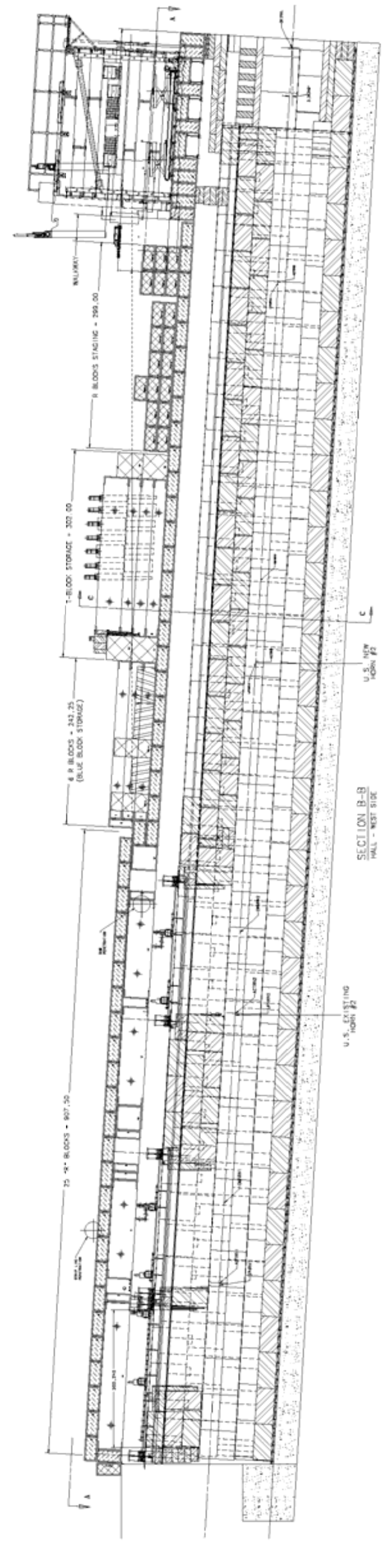


Figure 43: A longitudinal cross section of the target hall shielding

2.5.6.1 Existing Shielding Design & Re-Configuration Required for Medium Energy Operations

The target hall shielding is made up almost entirely of steel “blue blocks” stacked as shown in Figure 44. At the horn locations, the center three rows of blue blocks are replaced with the horn modules together with associated shielding blocks (T-blocks, end blocks and stripline block), as shown in Figure 45 for Horn 2. At the new Horn 2 location in the shielding pile, the center set of blue blocks (see Figure 44) will need to be removed (a total of approximately 12 blue blocks) to make space for the horn module. To greatly simplify moving Horn 2 to its new location, a new “dummy” horn module will be built identical in dimension to the existing design, but without all the associated penetrations, drive system, or horn support system. In the case where Horn 1 is re-designed and requires a new module, it might be possible to re-use its old module for Horn 2. In addition, an identical set of shielding blocks (T-blocks, end blocks, and stripline block) will be built, although the end blocks will probably be different and custom fit depending on the new interface condition. This “dummy” module assembly will essentially act as a shielding plug and work could begin on its installation during the 2009/2010 shutdown.

Once Horn 2 is ready to be moved, it will simply require swapping of the two module assemblies. It should also be noted that a new Horn 2 carriage and T-Block support tube weldment will have to be built and surveyed into position. Another advantage of having two module assemblies is that it will allow Horn 2 to be moved back to the low energy position if the need arises in the future.

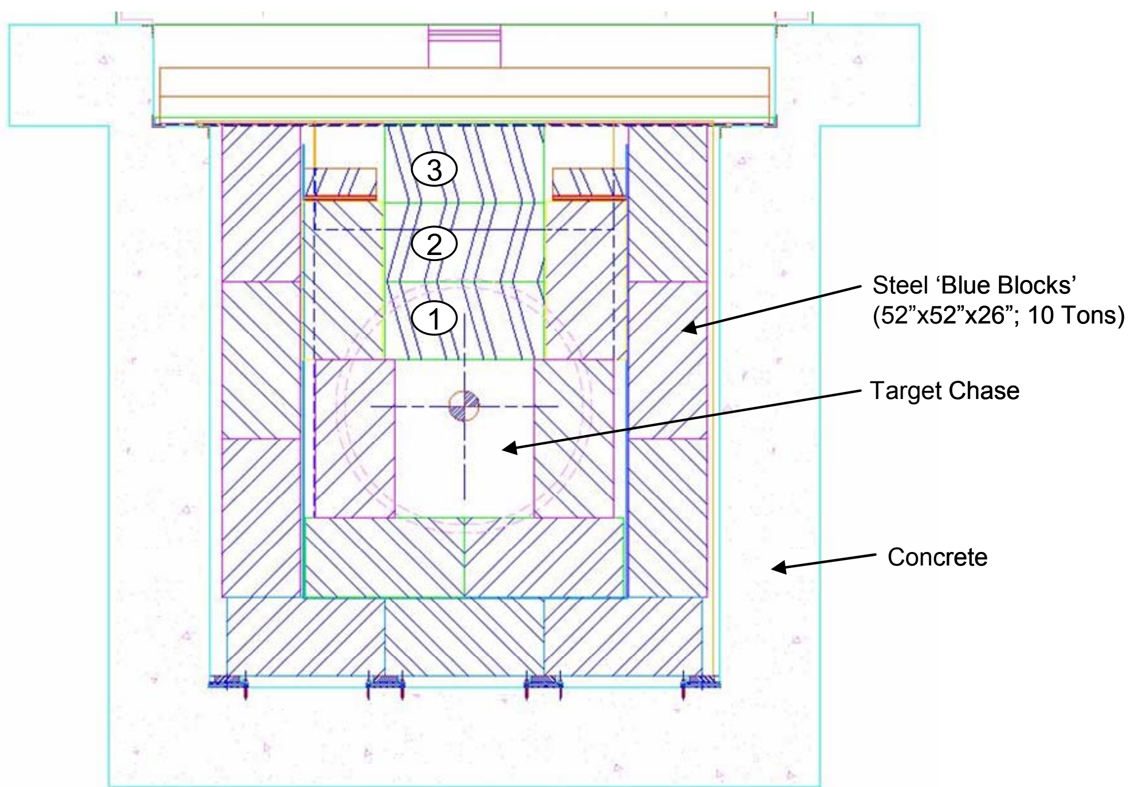


Figure 44: Typical NuMI Target Hall shielding cross section. At the new Horn 2 position, only the center row of blue blocks (marked 1, 2, & 3) will have to be removed.

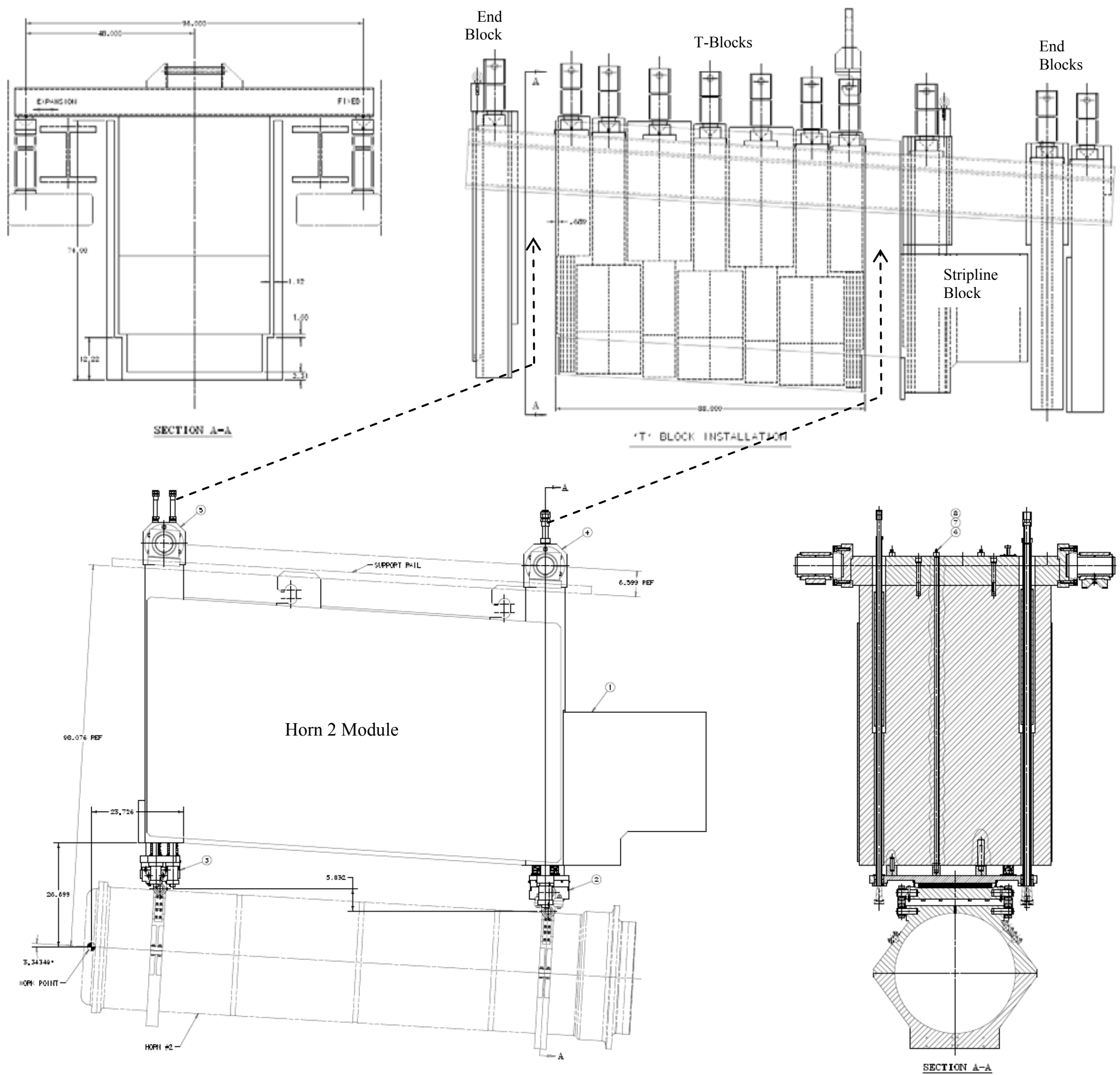


Figure 45: NuMI Horn 2 module and shielding blocks (T-blocks, end blocks, & stripline block). A new identical but simplified "dummy" module assembly is proposed that can be installed in both locations and act as a shielding "plug".

Another shielding alternative is to try to re-use some of the blue blocks at the vacant upstream position in place of the new T-blocks, however the custom end blocks will still be required. Up to six blue-blocks could be re-used with this scheme, but it will greatly depend on ease of use of the remote handling system, also discussed in the next section. Remote stacking of blue blocks needs further study and actual test runs need to be carried out to ensure it can be done effectively.

2.5.6.1.1 Blue Block Storage & Remote Handling

During the Horn 2 move, a certain number of surplus blue-blocks will be taken out from the new location. These could then either be completely removed from the target hall (the ideal scenario) or stored in some fashion within the available target hall space. A detail radiation survey needs to be first conducted to measure the residual dose rates. If dose rates are reasonable, a coffin can be designed to safely remove and transfer some of the blue blocks to an external storage site (weight and size of the coffin will be the limiting factor). The morgue could also be used as a temporary storage for hot blocks but this should only be considered a short-term solution. As mentioned earlier, some of the blocks could be re-used within the shielding pile itself (for example in place of the T-Blocks). Also, a couple of blocks could possibly be stacked on top of the existing three layers of blue blocks, assuming there is no interference with equipment. These options will all be part of the detail study on available space issues in the target hall.

If residual dose rates are high on some of the blocks, which will most likely be the case with the target chase blocks, then remote handling will be required. The existing remote handling lifting fixture and camera system are not adequate to do this task effectively. An assessment of the remote lifting system will have to be made requiring possible upgrades to the fixture and camera system.

2.5.7 Striplines

2.5.7.1 Stripline Extension

The original NuMI design concept was to have horn 2 capable of being moved into three discrete locations and provisions were made to extend the existing stripline in the future for the new horn locations. However, no stripline extensions were built so new ones are needed for the NuMI upgrade.

The stripline is the electrical connection between the 240 kA pulse power supply and the horns. The stripline consists of 8 layers of high conductivity 6101-T61 aluminum bus bars which are 12 inches wide by 0.375 inches thick. The bus bars are held together by aluminum clamps with fiberglass insulators in low radiation areas. The walkway stripline assembly is mounted to steel C-channels supported by steel stands. The walkway stripline extension will be pre-assembled in a building and then be installed in the target hall. On the downstream end of the existing walkway stripline in the target hall there are silver plated contacts that currently have four shunts plugged into. The shunts will be moved to the end of the new extension and the new stripline extension will plug into the end of the existing stripline. The two existing stripline assemblies, the chase and module striplines, which are under the R-blocks will be reused at the new horn 2 location.

The power supply is a 0.9 F capacitor bank that operates up to about 1 kV and the power supply output is presently set to 200 kA at 680 V. The two focusing horns, each a single turn air core magnet, are constructed in a co-axial configuration. The addition of 10 meters of stripline will increase the inductance of the system by 160 nH. The power supply voltage will have to be increased to about 787 V to maintain the 200 kA output. Even though there is an increase in power supply output the electrical heating of the stripline will increase only slightly due to 10 extra meters of stripline to dissipate the heat.

Beam heating of the horn and shield block striplines may be a problem and should be examined.

2.5.7.2 Stripline Cooling

Heating of the horn stripline is a concern for the NuMI upgrades. In the case of the stripline there are two contributions to the heating: beam energy deposition and the electrical current. For the analysis of the stripline cooling beam energy deposition values are scaled up from the NuMI values as explained in Section 2.5.8.2, "Target Chase Energy Deposition and Thermal Analysis", and the conductor power density values are scaled up from the NuMI values by multiplying them by (Proton Plan 2 RMS current / NuMI RMS current)^2. The RMS currents are based on 200 kA peak, a 2.3 ms long half since wave pulse, and pulse repetition rates of 1.872 seconds for NuMI and 1.333 seconds for Proton Plan 2. Conductor resistance is corrected for temperature using a temperature coefficient of resistance of 0.0038/^{o}C (at 25 ^{o}C.)

Stripline cooling is provided by the air circulating through the target pile. There are two flow paths. The first path is the flow in the chase. This airflow directly hits sections of the stripline that are not shadowed by Horn 1. These sections are cooled in the FEM by applying forced convection heat transfer coefficients. Sections of the stripline that are shadowed by horn 1 are cooled via natural convection in the FEM. Clamps on the stripline stop the airflow from hitting the conductors directly. Clamp areas in the FEM are cooled by conduction along the conductor to areas cooled by air. The second path is the airflow along each conductor as it runs through the channel in the stripline block. This flow is driven by the pressure difference between the top section of the target pile (under the R-block covers) and the chase.

The preliminary estimate for Proton Plan 2 Horn 1 stripline operating temperatures is shown in Figure 46. The estimate has been made using the finite element model (FEM) used to estimate the same temperatures for NuMI. The applied heat loads are shown graphically in Figure 47. The analysis is for a single conductor. The estimates show that a portion of the stripline reaches 166 ^{o}C. The highest temperature, estimated at 166 ^{o}C, is reached in the portion of the stripline near the beam axis but shadowed from the airflow by Horn 1.

Further analysis of the stripline heating is planned and additional cooling may be needed. The additional cooling might be implemented by redirecting the airflow in the region downstream of the horn to increase the convection cooling.

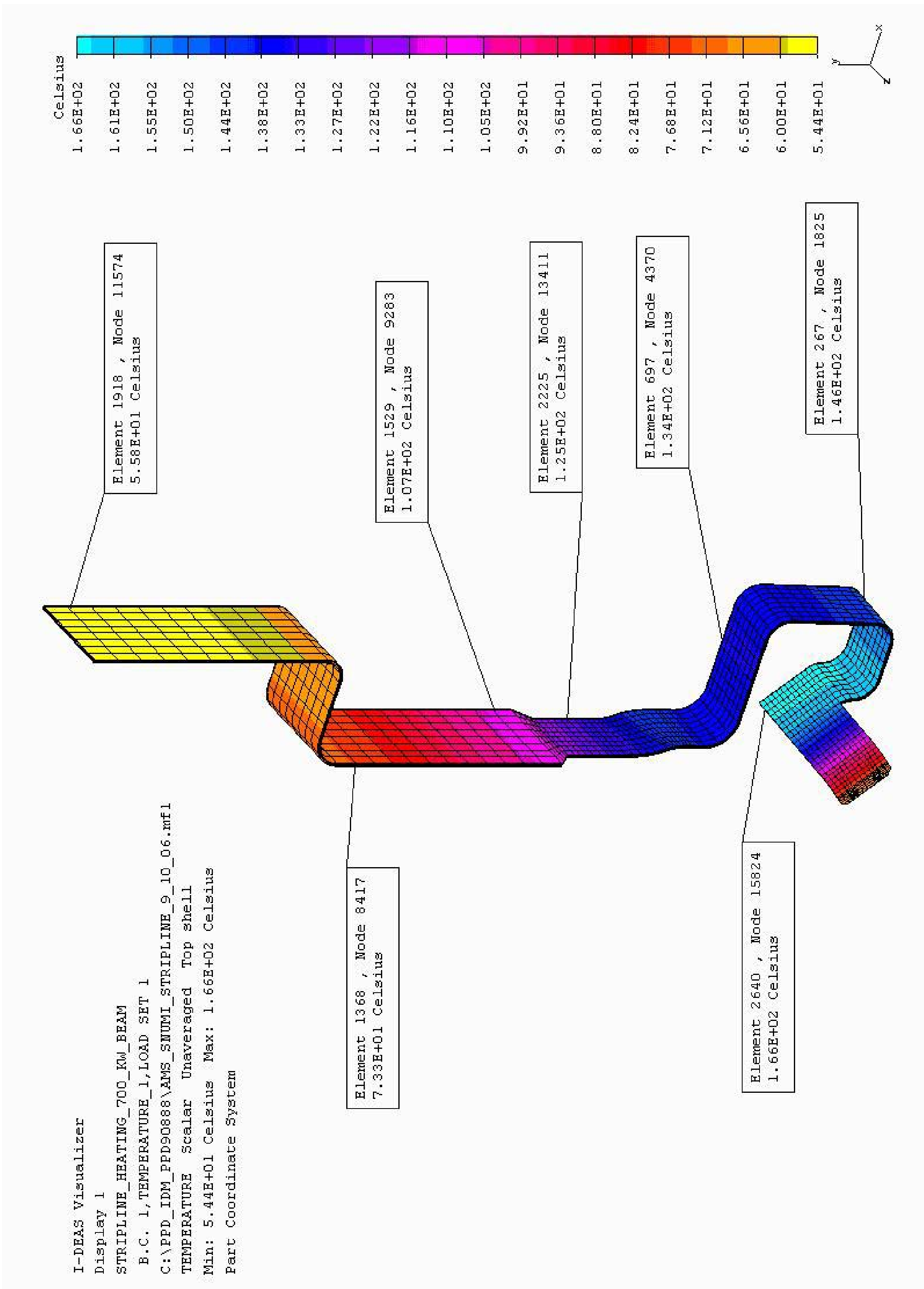


Figure 46: Preliminary estimate for Proton Plan 2 horn 1 stripline temperatures using NuMI FEM.

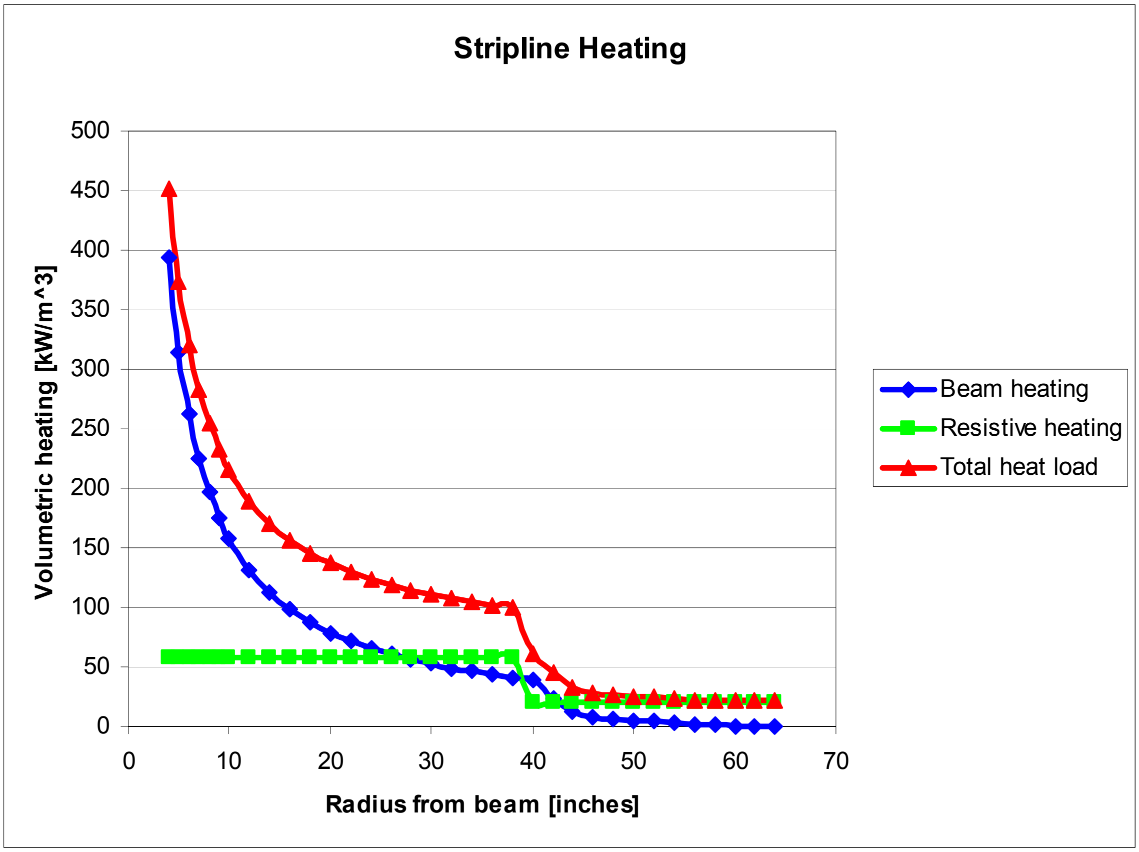


Figure 47: Applied heat loads for the stripline temperature FEA results in Figure 46.

2.5.7.3 Stripline Block

The stripline block (or Shield Block Main Assembly) provides a path that the stripline bus takes through the steel shielding in the horn module. The stripline takes two 90° turns in the shielding blocks as shown in Figure 48. This labyrinth prevents the radiation from having a direct unobstructed path to above. Cooling air comes down from above, through the stripline shielding block labyrinth, to cool the stripline.

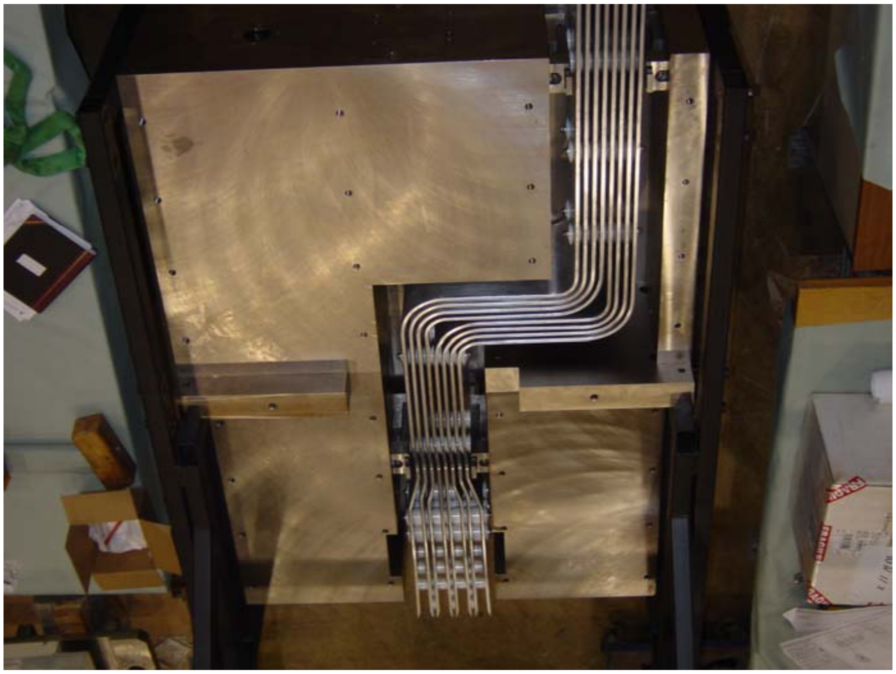


Figure 48: Shield Block Main Assembly. Shown with the cover removed

At the bottom of the shielding blocks is the Remote Clamp Assembly shown in Figure 49. The clamp makes the connection between the stripline within the module and the stripline attached directly to the horn. Figure 50 shows a photo the horn stripline attached to the stripline block. The clamp is operated remotely from above the module due to the high levels of residual radiation. There is a mechanism that will either push or pull stripline connection at the remote clamp. This will ensure that the contacts have the correct amount of overlap when the clamp is tightened and if the contacts seize closed, it can force the joint apart.

The stripline overlaps with about 9 square inches of silvered contact area on each bus bar. Approximately 3600 pounds of force on each of 5 pairs of ceramic plungers provides a total of 18,000 pounds of clamping force. This yields an average of 2000 pound per square inch on the silvered contact surfaces. The 12-inch wide bus on the Shielding Block Stripline Assembly necks down to 8 inches wide at clamp. The shielding block stripline is insulated by ceramic insulators in the high radiation areas. Above the shielding blocks fiberglass is used as an insulator for the stripline.

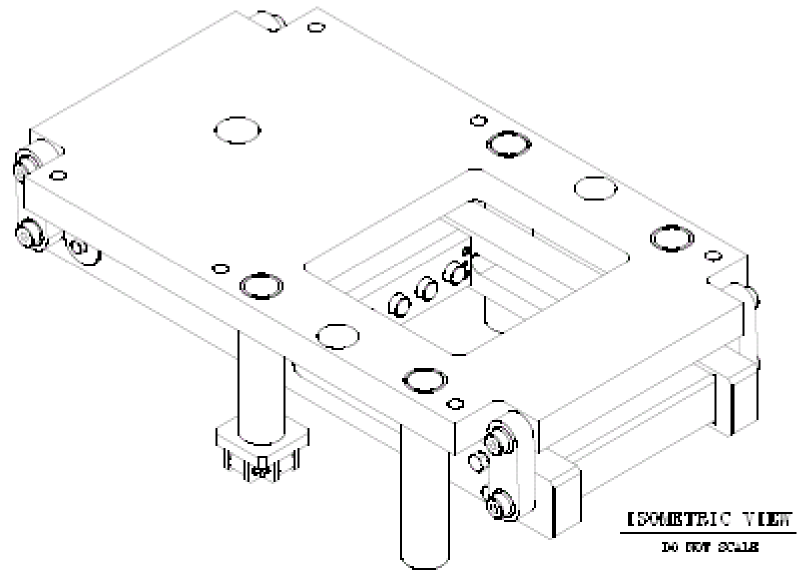


Figure 49: Isometric view of the clamp. Three of the five plungers are visible.

The shielding block stripline normally stays connected to the module with the horn because the silver plated aluminum connection will degrade with use and there is a possibility of getting debris in the joint. The silvered contacts have thin layer of Dow Corning silicon grease that reduces corrosion and provides lubrication in the low radiation areas. One problem is grit from the concrete R blocks can get on the silvered contact surfaces and cause problems. A through cleaning of the contact surfaces is needed on reassembly. There is no grease used in the high radiation area.

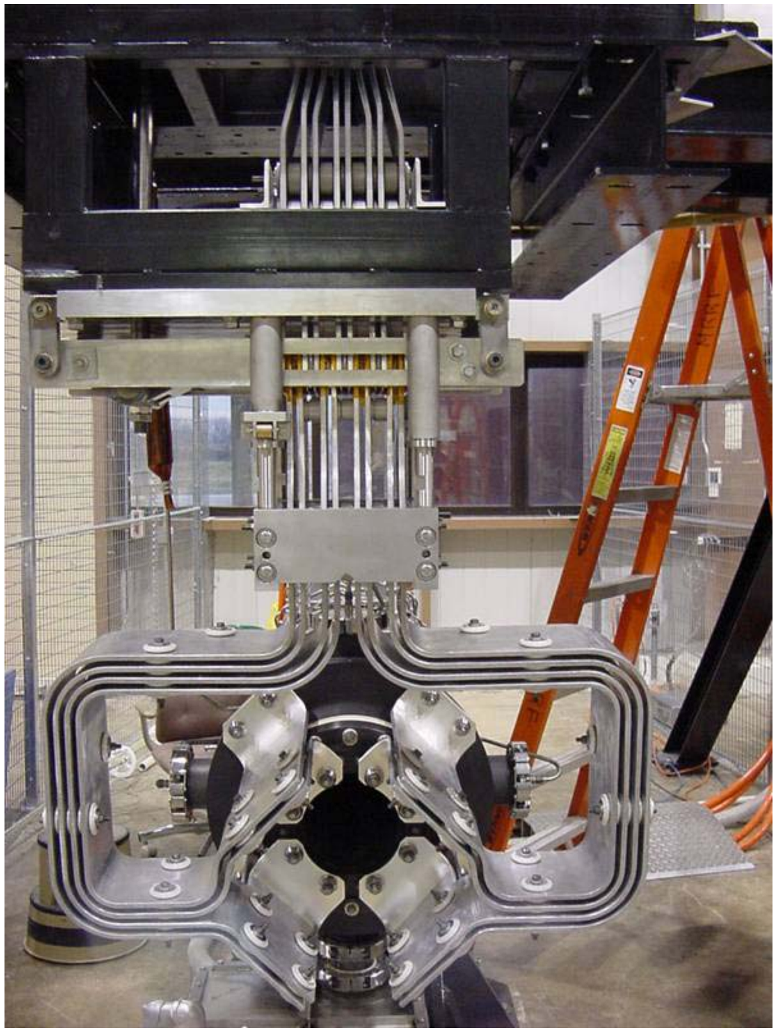


Figure 50: Photo of the horn stripline shown attached to the horn and extending up into the horn module.

2.5.7.4 Stripline Block Cooling

The stripline is narrower and thinner at the clamp location and there is additional resistive heating at the contact area. It is not known if beam heating in the remote clamp area will be a problem at the higher power and further analysis is needed. An air passage drilled through the shielding blocks could be used to cool the stripline at the remote clamp and also to blow debris off of the stripline connection.

It will have to be determined if the bottom of the stripline shielding blocks will get too thermally hot from beam heating. We might have to water cool the bottom of shielding blocks or cool the remote clamp mounting plate which would act as a heat sink for the Shield Block Main Assembly.

2.5.8 Target Chase Cooling

2.5.8.1 Specifications

Cooling of the target chase is needed due to the large amount of beam energy deposited. With the 700 kW of beam power in Proton Plan 2 approximately 280 kW is deposited in the target pile. Maintaining a reasonable temperature in the target chase is important for several reasons:

- Thermal expansion of the target chase and target hall components will affect the alignment of the target and horns. The NOvA experiment requires that alignment of the beam, target, and horns remain within a 1.5 mm tolerance [75].
- The target pile consists of stacked steel blocks (referred to as "Blue Blocks"), which are painted to reduce corrosion. Burning and smoldering of the paint can be a problem if the target pile becomes too hot.
- Higher temperatures and radiant heating from the target pile can add to the heat load of target, horns, and striplines. This can lead to unacceptable temperatures of the target hall components.

Testing of the paint samples is planned to determine the temperature requirements in the target chase. Further analysis is also planned to determine the maximum acceptable operating temperatures for the target hall components.

2.5.8.2 Target Chase Energy Deposition and Thermal Analysis

A preliminary estimation of the expected target chase temperatures has been performed. The beam energy deposition values used in this analysis are scaled up from the NuMI values by multiplying them by 1.75 (which is the ratio of 700 kW to 400 kW.) The preliminary estimate for Proton Plan 2 target pile shielding temperatures is shown in Figure 51. The highest shielding temperature is 115 °C at the peak beam heating location just downstream of the Horn 1 location. The estimate has been made using the refined NuMI target pile finite element model (FEM).

The original NuMI target pile FEM was refined by incorporating the actual average heat transfer rate from two Duratek shielding blocks in the inner chase wall. The average rate was experimentally determined by monitoring the temperature of the two Duratek blocks as they cooled down with no beam heating and with the fan on. Both of the Duratek blocks are at the location of the theoretical peak of beam heating which is just downstream of horn 1; the blocks are on opposite sides of the chase directly across from each other. Each of these blocks has a thermocouple welded to it that was used to monitor block temperature during the test. The light blue colored block in Figure 51 is the one with the thermocouple welded to it on that side of the chase.

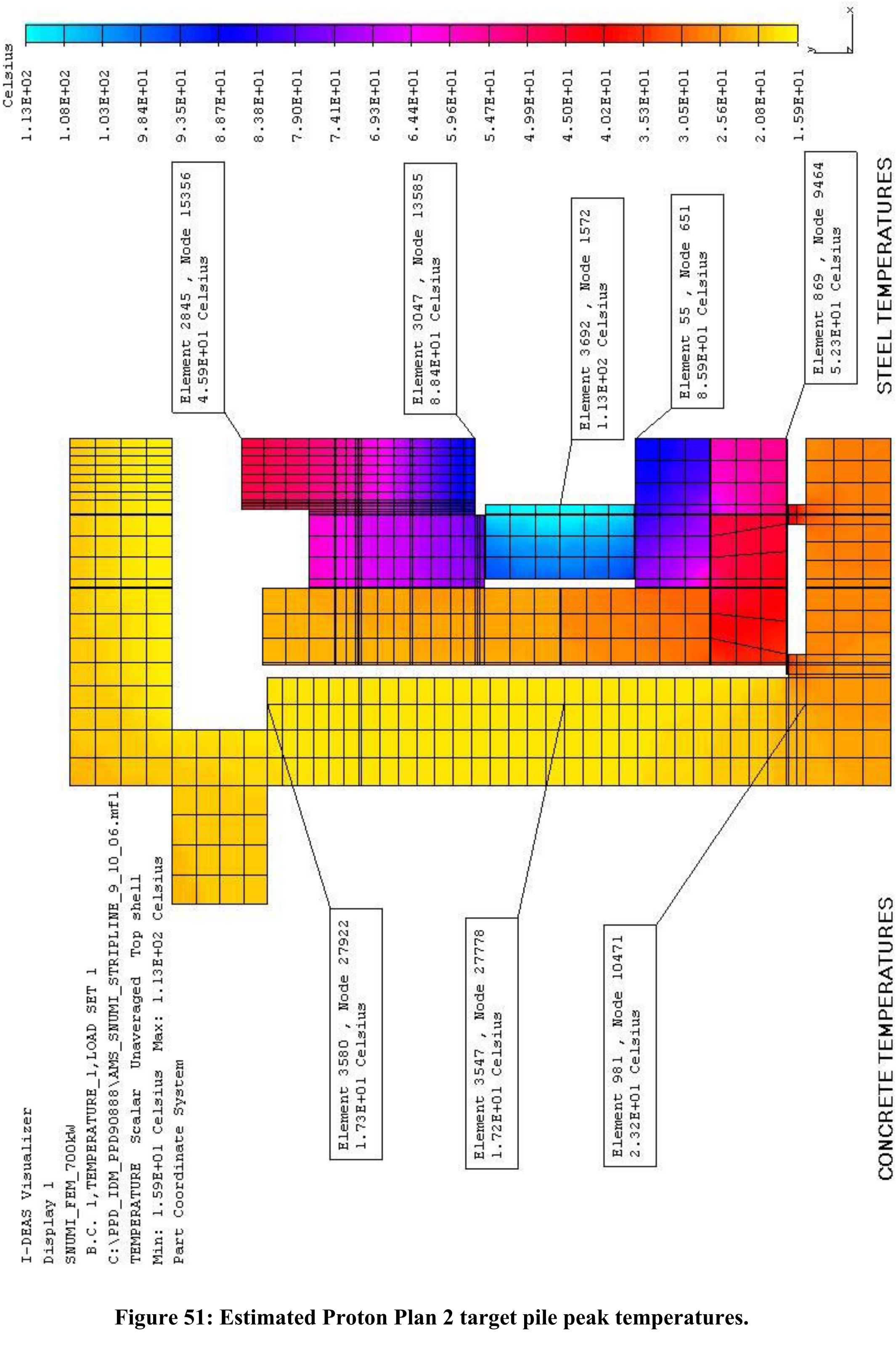


Figure 51: Estimated Proton Plan 2 target pile peak temperatures.

Concrete temperatures estimated using the NuMI FEM are slightly higher than expected because in the model the concrete liner is insulated at its outermost boundary where it contacts water-bearing rock instead of modeling it as a semi-infinite solid.

Based on this estimate we should be able to meet the alignment tolerance of Horn 1 based on the latest estimates of the motion of Horn 1 due to thermal effects [59, 60]. Further study of the paint characteristics and target hall components is needed to determine if the temperatures will be acceptable.

2.5.8.3 Air Cooling Modifications

The existing target pile air cooling system is designed to remove 240 kW from the air circulating through the target pile. The target pile heat loads are: 160 kW generated in the target pile shielding by the 400 kW NuMI beam, 2.5 kW resistive heating generated by the striplines, 55 kW generated by the circulating fan, 19 kW associated with inward air leakage, and 3.5 kW ambient heat leak. Increasing the beam power from 400 kW to 700 kW and the increased stripline resistive heating adds an additional 125 kW to the target pile heat load for Proton Plan 2.

To handle the increased heat load two coils will be added to the existing system to remove the additional 125 kW generated by operating NuMI with the 700 kW beam (Proton Plan 2). Preliminary calculations to estimate the size of the new coils are in reference [63]. The modified system is shown schematically in Figure 52.

The new coils transfer the 125 kW from the air circulating through the target pile to the existing secondary chilled water loop. The secondary chilled water loop will be upgraded to handle this load; the upgrade is discussed in Section 2.5.9.2, "MI-65 Secondary Chilled Water (SCHW) System". The 240 kW design load for the 400 kW NuMI beam is rejected to the LCW system using a chiller. The chiller loop will continue to transfer this load for Proton Plan 2 without modification.

The two new coils will be placed in the existing coil box upstream of the existing chiller coils after the coil box is modified to accept the new coils. The modifications are minor because there is additional space in the coil box immediately upstream of the chiller coils. This space was made as large as possible in the original design to provide for future expansion. Part of the space is currently occupied by dampers which are no longer needed (see Figure 53.) The air-cooling system was originally designed for variable speed operation of the air circulation fan and the dampers were needed to control coil velocities at low fan speeds. Minimum fan speed was subsequently set high enough during commissioning to obviate the need for the dampers. They are held wide open for NuMI operation and can be removed without degrading system performance. The existing chiller coils must be temporarily removed from the coil box to make room for the sheet metal workers. The coil box is downstream from the filters and experience has shown that radioactive particulate matter does not enter the coil box. Thus, it is anticipated that the coil box does not have to be decontaminated for this work but this needs to be determined at the time the modifications are made.

The coil box modifications are: remove the damper support rails, install structural support for the new coils using 2"x2"x $^{1}/_{4}$" 304L stainless steel angle, add drain lines to the condensate tray for the upper coil or install a new condensate drain port (2" 304L stainless steel pipe coupling) in the sidewall for this section of the coil box, cut holes in the existing cover for the chilled water piping, and install four 1” stainless steel pipe couplings for new temperature sensors between the new coils and the chiller coils. No modifications are needed to drain the lower coil because it drains into the existing condensate sump through a ½” high by 72” wide internal slot. The four coils are shown mounted schematically in Figure 54.

The calculations summarized in Figure 52 show that no condensate forms at the exit of the new coils at full heating load. Condensate drainage for the new coils will be provided in case condensate forms at part load operating conditions.

The two new coils are connected in parallel in the secondary chilled water loop. The water flow to each coil is controlled with a control valve under automatic PID control. Air discharge temperature downstream of the new coils will be controlled between 24 ^{o}C to 20 ^{o}C. Process variables that will be measured and transmitted to the target pile PLC and displayed on ACNET are: water flow for each new coil, chilled water exit temperature for each new coil, air exit temperature for each new coil, and chilled water temperature on the common supply line. Local instruments will display the temperatures that are transmitted to the target pile PLC, the chilled water pressure drop across each new coil, and chilled water supply pressure.

The air circulation rate through the target pile for 700 kW beam will be the same as the rate currently used for NuMI. This airflow rate is 25,000 scfm. The fan operates at 1455 rpm for NuMI; maximum fan speed is 1750 rpm. Pressure drop across the new coils is estimated to be 1” wg, same as for the chiller coils. Based on current system performance the fan can provide, by increasing the speed 5%, 25,000 scfm with the current operating pressure differential increased by 1” wg. No changes are planned for the air circulation fan except for increasing the speed to make up for additional pressure drop.

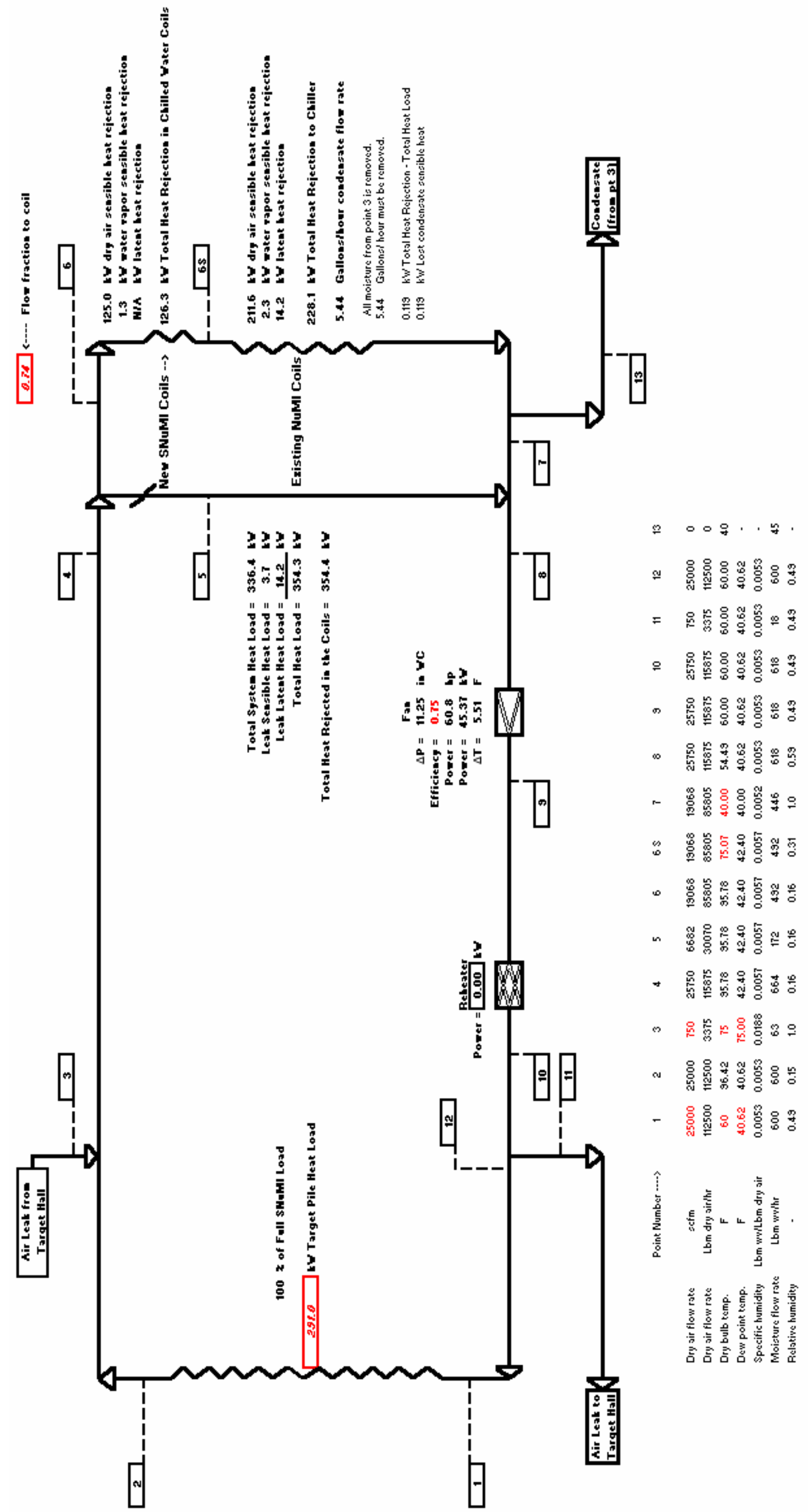


Figure 52: NuMI flow schematic modified for Proton Plan 2 operation at 700 kW beam power. Point 6S has been added to show exit conditions for the new coils.

Figure 53: Space in the existing coil box for one of the new coils. The two pairs of rails that run across the coil box (one pair above and one pair below) currently hold a damper in place. The black surface to the right is the epoxy coated chiller coil.

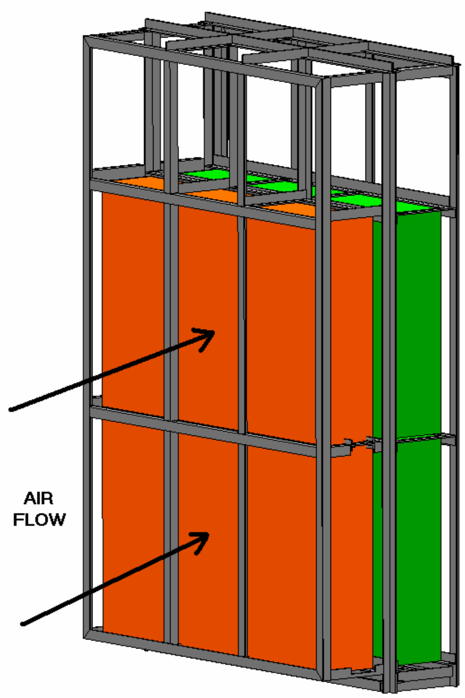


Figure 54: Coil box frame with sheet metal removed. New coils (orange) will be installed upstream of the chiller coils (green). Passage above the coils is for the bypass air flow.

2.5.9 (Non RAW) Cooling Water Systems

There are three primary water-cooling systems used for NuMI. These cooling systems serve power supplies in the Main Injector and Primary Beamline areas, the RAW water systems in the target hall, the target hall air-cooling system, and decay pipe and absorbers RAW systems.

Of the three water-cooling systems, only the heat exchanger on the MI-65 Secondary Chilled Water (SCHW) system needs upgrading before running NuMI at 700 kW.

2.5.9.1 MI-62 Low Conductivity Water (LCW) System

Currently this system serves heat loads in the main injector, extraction enclosure, pre-target area, power supplies in the below grade power supply room and in MI65, the target pile chiller and the target area raw skid. Refer to Table 17 for a summary of these heat loads. Modifications to this system for the Proton Plan 2 700 kW upgrade are considered to be minimal.

Systems Served by MI-62 LCW (Pond-H)	Estimated Heat Loads NuMI (400 kW beam power)	Estimated Heat Loads Proton Plan 2 (700kW beam power)
MI-62 LCW Pump	51	51
MI-62 Power Supplies	13	13
MI-NuMI Extraction Stub	450	471
Pre-Target Enclosure	190	196
MI-65 Target Service Bldg	33	40
Horn Power Supplies	12	18
Target Pile Chiller Coil[3]	380	380
Target RAW[3]	20	20
Total	**1150**	**1200**

Table 17: System served by the MI-62 lCW system. The capacity of the LCW system is 1.2 MW.

The existing Main Injector cooling pond that provides heat rejection for the LCW system is Pond H. It is approximately 1.1 acres and was initially designed to serve a 550kw heat load through pump vault PV9. PV9 was modified during the NuMI construction project and has flow characteristics of 820 gpm with 90 ºF CPWS and 100 ºF CPWR. PV9 flow is routed to buildings MI62, MI65 and MI8. There are no connected loads currently in MI65 or MI8.

It is noted that the extra load will increase the temperature of Pond-H by about 1 degree. Pond-H is already somewhat problematic during summer months and can reach temperatures above the desired 95 degrees of the LCW system. Further analysis of Pond-H heating is continuing and more results can be found in [64].

2.5.9.2 MI-65 Secondary Chilled Water (SCHW) System

The current configuration of the secondary chilled water (SCHW) system consists of primary and standby 7-1/2HP pumps, a heat exchanger (HX) located on the mechanical mezzanine of the MI65 service building, 4” piping that traverses down the shaft and to the below grade service rooms. Heat loads rejected to this system include the power supply room fan coil unit, the decay pipe cooling skid, Horn 1 skid, Horn 2 skid, and the target pile chiller. Refer to Table 18 for a summary of these heat loads.

Heat from the heat exchanger is rejected to the Central Utility Building (CUB) chilled water system. The current SCHW pump has a flow and head capacity of 212 gpm at 60 fthd. The heat exchanger was designed with the following parameters: CUB chilled water ewt 45 ºF/lwt 55 ºF at 215 gpm; SCHW ewt 60 ºF/lwt 50 ºF at 212 gpm with a 310 kw capacity.

Systems Served by MI-65 SCHW	System Capacity (kW)	Proton Plan 2 (700kW) Heat Load (Estimated kW)	Comments
Horn 1 RAW	72	53	Horn 1 RAW info missing. Horn 1 heat load
Horn 2 RAW	72	18	Horn 2 heat load may be higher in the ME location.
Decay Pipe RAW (Upper)	80	116	Scaled from MARS simulations of NuMI Design (400kW)
Fan Coil Unit	60	105	Cools the NuMI power supply and RAW rooms
Target Pile Chiller Heat Exchanger	28	28	No Change for Proton Plan 2 Upgrade
New Target Pile Air Handling Unit	N/A	125	New for Proton Plan 2Upgrade
Total		**440**	

Table 18: Systems served by the MI-65 Secondary Chilled Water. The total estimated heat load of 440 kW is greater than the current capacity of 310 kW.

This system will be modified to provide additional cooling as required by Proton Plan 2. The above described pumps and heat exchanger will be replaced or modified to meet the new heat load requirements. As a minimum additional flow of approximately 100 gpm at 50 ºF will be provided to the target chase air handling unit. A detailed description of this unit is located in Section 2.5.8.3, “Air Cooling Modifications”. This piping will be routed to the target hall through the utility passageway above the labyrinth.

2.5.9.3 NuMI Sump Water Cooling

At the MINOS underground area heat is rejected to the water collected from tunnel inflow. The current inflow, measured in Oct 2006, is 165 gpm down from the initial flow of 235 gpm at occupancy in March 2004. Electronics equipment in the MINOS detector hall rejects heat to the 165-gpm ground water system through an LCW system and to air through fan coil units located in the hall. A portion of this flow, approximately 75 gpm, is then pumped to the Absorber area where the ground water is routed through an intermediate RAW skid for the hadron absorber and the decay pipe chiller in series. Refer to Table 19 for a summary of these heat loads. The intermediate Absorber RAW system was designed with a capacity of 210 kW and will not need to be upgraded.

Systems Served by MI-62 LCW (Pond-H)	**Estimated Heat Loads NuMI (400 kW beam power)**	**Estimated Heat Loads Proton Plan 2 (700kW beam power)**
Decay Pipe RAW	82	116
Intermediate Absorber RAW	60	105
Total	**145**	**220**

Table 19: System served by NuMI tunnel sump water.

2.5.10 RAW water systems

NuMI uses 6 RAW skids and 1 intermediate RAW skid to cool the target, horns, decay pipe, and hadron absorber. Until a final determination is made of the heat load for each system it is assumed that all of the RAW systems will need upgrading. In any case there are plans to upgrade the instrumentation of the RAW skids to include remote readback of the temperature and flow measurements. Preliminary estimates of the necessary upgrades are listed below:

Target RAW System: Initial calculations suggest that the target RAW skid will be sufficient for Proton Plan 2, but final determination awaits a report from IHEP on the heat load of the medium energy target design. The skid will be upgraded with modern instrumentation and controls. It is possible that the system will be modified to incorporate a bubbler system which protects the target water cooling lines from thermal shock.

Horn 1 RAW System: It is likely that the Horn 1 skid will need an upgraded to handle the higher heat load for Proton Plan 2. In addition to circulating the cooling water, the pump on the RAW skid also powers the ejector pump which removes water from the collection tank below Horn 1. Presently the ejector pump is barely adequate for the purpose of removing water from the holding tank. Therefore, the Horn 1 RAW system will be equipped with a larger water pump and the ejector pump for Horn 1 may be redesigned as well.

Horn 2 RAW System: Initial calculations suggest that the Horn 2 RAW skid will be sufficient for Proton Plan 2. The skid will be upgraded with modern instrumentation and controls. The water lines between the RAW skid and Horn 2 will be extended to reach the new location of Horn 2.

Decay Pipe RAW (upper skid): An upgrade is planned for the Decay pipe RAW skid that is located in the RAW room in order to handle the higher heat load for Proton Plan 2. The skid will be upgraded with modern instrumentation and controls.

Decay Pipe RAW (lower skid): An upgrade is planned for the Decay pipe RAW skid that is located in the auxiliary tunnel near the absorber hall in order to handle the higher heat load for Proton Plan 2. The skid will be upgraded with modern instrumentation and controls.

Absorber RAW System: The absorber raw system will need will need upgrading to handle the higher heat load. In addition, there is an **Intermediate RAW System** inserted between the Absorber RAW system and the NuMI groundwater cooling. This provides an extra measure of protection by isolating the absorber RAW water from the groundwater. This system will also be upgraded.

2.5.10.1 RAW Room Layout

The present RAW room is expected to have enough space to handle the upgrades to the RAW systems. If necessary, some extra space could be created by moving the chiller closer to the power supply room and extending the RAW room into the area no occupied by the chiller.

2.5.11 Decay Pipe

The NuMI Decay Pipe is a 2 m diameter, 670 m long, evacuated steel pipe surrounded by concrete. It is terminated at the upstream end with a thin composite steel/aluminum vacuum window and a thicker steel head at the downstream end. The potential of failure of the windows and the pipe were investigated by modeling the structures using finite element analysis and using energy deposition simulations from the MARS package.

The worst case scenario, the "fault condition" used in all of the decay pipe calculations, is considered an improperly steered primary proton beam which cleared both the baffle and target and therefore hit the upstream decay pipe window directly. The size of the beam at the upstream vacuum window, due to divergence, was a 1.6 mm sigma Gaussian distribution in x and y. A maximum of 10 beam pulses under the fault condition is allowed.

2.5.11.1 Decay Pipe Window

The NuMI decay pipe is a 72 inch diameter upstream end closure consisting of a 1 m diameter, 1/16 inch thick aluminum central portion, transitioning to a 3/8 inch thick steel head at the larger diameters. This transition is achieved with an explosion-welded aluminum-to-steel flange. This structure is not actively cooled. The heating and stresses in the central portion were investigated using an axisymmetric finite element model with approximately 800 four-node elements. A thermal version of the model was used to calculate the temperature profile in the head; a structural version of the model then read the temperature profile to calculate stresses. The rules for the allowable stresses were taken from the ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2, Appendix 4. The loading to the thin window is due to vacuum and the cyclic thermal stresses resulting from beam energy deposition.

The primary issue is the weakening of the 6061-T6 aluminum at high temperatures. Also, this alloy becomes progressively weaker if held at high temperature for long periods of time, so that any operation above 150 °C must be of short duration, less than 6 minutes. The criterion for acceptable behavior under fault conditions is that the window does not experience strains beyond the proportional limit, i.e., plastic strains. The following procedure was used to determine the maximum allowable steady-state beam energy. The MARS-based energy deposition (fault condition) was scaled and the resulting temperatures and stresses examined after ten cycles. The beam deposition was then adjusted until no plastic strain was calculated.

The results of the engineering calculations are:

- To prevent any plasticity the beam power is limited to 1700kW
- It is critical to limit the number of fault cycles
- Normal operation is benign
- The temperature rise in the thick downstream window is not of concern

The vacuum windows are acceptable as-is under Proton Plan 2 loads of 700kW providing that the fault conditions are limited to ten cycles [65].

2.5.11.2 Decay Pipe Cooling

The decay pipe consists of a 2 m diameter A36 steel pipe, 0.375 inches thick, 670 m long, encased in a cylindrical shell of concrete varying in diameter from 4.6 to 6.3 meters. In use, the steel pipe is evacuated. The decay pipe is cooled by twelve tubes, evenly spaced azimuthally, and running parallel to the steel pipe, but attached directly to the pipe only at the stiffening rings, which are spaced ten feet apart. The tubes comprise six distinct circuits. Six tubes bring chilled water from the downstream to the upstream end, where it is re-chilled and returned. The design flow rate of each circuit is 4.5 gallons per minute, for a total system flow of 28 gallons per minute. The water temperature leaving the chiller is 25 °C.

The heat generated in the pipe and concrete under a 2 MW load was calculated using MARS. Two radial bins approximately 5 mm wide were used in the steel pipe. Radial bins 100 mm wide were used in the concrete. Both components used 1 m long bins in z. It can be shown that of the 750 kW deposited in the two materials, 52% (390 kW) is deposited in the steel pipe, and the remainder (360 kW) in the concrete.

The radial clearance assumed to exist between the concrete and the steel pipe affects both the heat transfer (which is better for small clearances because of the reduced thermal resistance) and the hoop stress in the steel pipe (which is better at large clearances because the steel pipe is free to expand without being constrained by the concrete.) For this analysis, two clearances were considered in detail: Zero, and 1 mm. It can be shown that thermal-expansion induced hoop stress is a maximum when the clearance is zero; for a 1mm clearance, the temperature of both the steel pipe and concrete increase, but the two components are far enough apart that they do not interact radially, and the hoop stress is nearly equal to that of the vacuum load alone. For this analysis, the steel and concrete were both assumed to be perfectly constrained against axial expansion at both ends. The purpose of the analysis was to determine whether the pipe (which is virtually impossible to now modify in any meaningful way) can safely dissipate this quantity of heat.

The four parameters most directly affecting the stresses in the pipe are the radial clearance (and consequent heat transfer) between the concrete and the steel pipe, the degree of axial constraint at the ends of the pipe, the outer boundary cooling provided by the ground water, and the flow rate and bulk temperature of the cooling water. Results show that, with a doubling of the design cooling water flow rate, and under the assumption of 1 mm of air between the steel pipe and concrete, the maximum temperature of the decay pipe and concrete will not exceed 117 °C. Under the assumption of zero clearance between the concrete and steel (not unreasonable, given the shrinkage of concrete), the maximum temperature should not exceed 96 °C. The constraint of the concrete on the steel pipe raises the buckling stress far above 36 ksi, the yield stress of the steel. All calculations show that actual hoop stresses do not exceed 26 ksi. The axial stress necessary to buckle the steel pipe is also well above the yield stress. The calculations show that axial expansion of the pipe against the constraints at its end will not produce axial stresses in excess of 31 ksi. The slow warming of the system (about 200 days under a continuous 750 kW heat load) will permit the water in the concrete to migrate out of the matrix and evaporate without causing steam buildup and explosive spalling against the pipe.

The calculations conclude:

- The system can withstand 2 MW loads without danger of failure
- The cooling system is assumed to upgraded from 4.5 to 9 gpm per circuit

The Decay Pipe is acceptable under the Proton Plan 2 loads of 700kW (and higher) assuming that the flow of cooling water is doubled. Supporting references for the decay pipe can be found in [76, 77, 78].

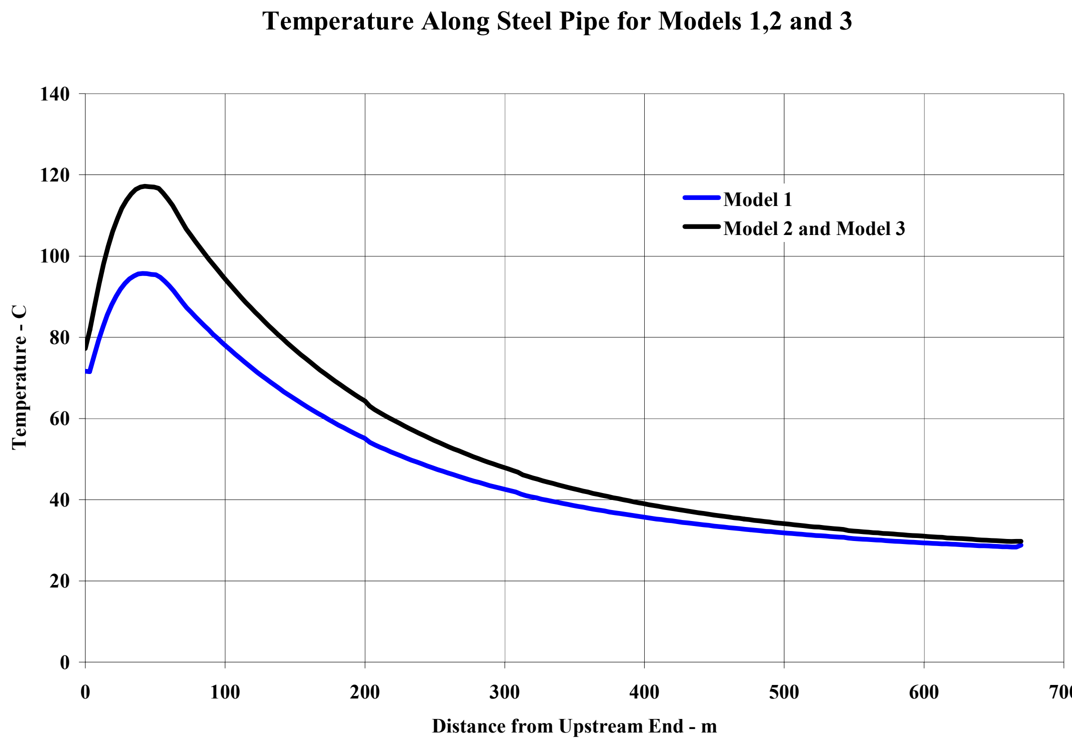


Figure 55: The temperature of the pipe with 2 MW beam power, 2.8 times the design beam power of Proton Plan 2. Model 1 shows results with 1mm assumed clearance between pipe and concrete and Model 2 assumes zero clearance.

2.5.12 Hadron Absorber

2.5.12.1 Energy Deposition and Stresses in the Absorber Core

The NuMI hadron beam absorber core consists of nine water-cooled aluminum modules, 1.32 x 1.32 x 0.31 meters in size. This design was also analyzed by IHEP [79]. The (present) NuMI design criteria require that the absorber operate for one hour (approximately 1800 pulses) under the fault condition. The fault condition is defined as an improperly steered primary beam that misses the target and clears the baffle protection. Under normal operating conditions only about 18% of the 120 GeV primary protons strike the absorber, and the rms radial size of the beam is 20 cm compared to 5cm in the fault condition. The fault condition is the critical operating condition for the absorber system.

A MARS analysis shows that the fourth module absorbs the greatest energy, dissipating 58.5 kW under the fault condition. Under Proton Plan 2 beam loading, this energy will be increased to 103 kW. The detailed distribution was tabulated and made available to an ANSYS model, which was then used for the thermal and structural analysis.

In Proton Plan 2 the fault condition will be limited to a maximum of 10 pulses. The same engineering model indicates that the present NuMI hadron core can accommodate the increase in beam intensity (700kW or 1.75 times the original design intensity) without failure.

2.5.12.2 Absorber Cooling System

The performance of the present NuMI absorber system is consistent with the design calculations. The cooling water temperature rises about 2.4 °C with a 250 kW beam load. Scaling to Proton Plan 2 beam loads the absorber cooling system can accommodate the increase under normal operation. The maximum absorber temperature is not achieved until several hundred pulses, since it is so massive. The ten (maximum) fault pulses allowed in Proton Plan 2 does, over 13.3 seconds, not pose a significant problem for the cooling system.

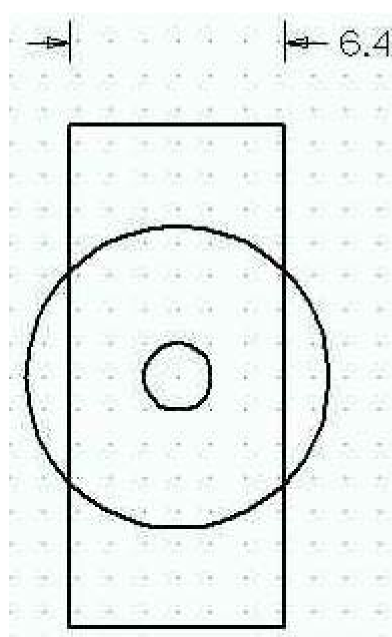
The hadron absorber system does not require modification for continuous operation with 700 kW beam loading. The maximum number of fault pulses allowed is ten. Supporting references for the absorber can be found in [80, 81, 82]

2.5.13 Instrumentation

2.5.13.1 Beam Permit System

Additional input to the beam permit is desired in order to add another layer of protection for the decay pipe window. No more than 10 beam pulses in a row should be allowed to miss the target and reach the decay pipe window.

The Beam Position Monitor system currently pulls the beam permit if a beam pulse is off center by more than +/- 1.5 mm, which prevents more than one mis-steered beam pulse in a row reaching the decay pipe window through the opening between the target and baffle. However, software and hardware glitches can happen that make this less than 100% effective, and the effect of damaging the decay pipe window would be extremely serious.



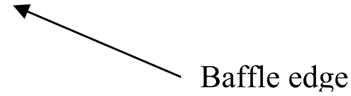


Figure 56: Beam spot, target and baffle alignment in ideal case.

At radii larger than baffle hole, the decay pipe window is protected by the baffle; the target protects the baffle for small offsets of horizontal position (see Figure 56). There is a small region between the two where un-interacted beam could reach the decay pipe window.

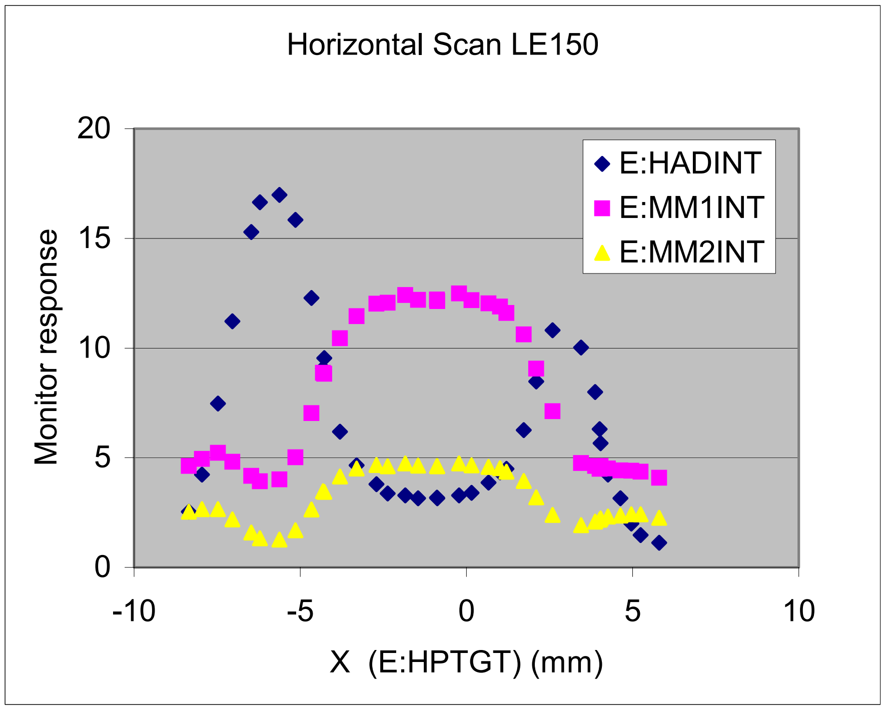


Figure 57: Hadron and muon monitor response as a function of beam position, taken June 1, 2006 with target in a semi-medium energy position relative to horn 1.

The response to beam offsets of three existing beam monitors is shown in Figure 57. The hadron monitor gives a very clear jump in response when beam goes through the crack between target and baffle, and thus putting it in the beam permit is useful. The hadron monitor is however not 100% effective, since in an accident where beam is not only offset but also angled, the beam could miss the hadron monitor entirely.

One sees that the muon monitor response decreases as beam falls off the target, and this would be true even with an angled beam. A software process can be written which compares the muon monitor response to the toroid measurement of beam proton intensity, and would drop the beam permit if the muon/toroid signal were more than 20% below normal. The software would ignore the ratio if the toroid signal indicated no beam or very low intensity beam (less than $2x10^{12}$ protons/pulse).

The combination of beam position monitor, hadron monitor, and muon/toroid monitor will provide redundant protection for the decay pipe window.

2.5.13.2 ACNET

A test is needed to check that the ACNET front-ends will read out and data-log reliably with the 1.33 second repetition rate, compared to the current 2 second repetition rate.

2.5.13.3 Beam Permit System

As the power on the NuMI target is increased protection against accident conditions become more important. The present beam permit system will be augmented with additional inputs to protect against multiple accident condition pulse.

2.5.13.4 NuMI Decay Pipe Temperature Monitoring (WBS 1.4.3.1)

It is proposed to instrument the Decay Pipe Shielding to permit the measurement of the temperature of the Decay Pipe Shielding Concrete to study the heat retention, if any, of the concrete shielding, as a function of time and beam power.

In 2005 ten two-inch diameter holes were drilled on a slightly down sloping radius pointing to the center of the 6’6” decay pipe cylinder. These holes are located every 100 feet in the upstream region of the decay pipe passage. These were instrumented with a series of maximum temperature recording pinning dial thermometers, approximately five to a hole. The holes were drilled to a depth 1 foot radially outwards from the ½ inch thick decay pipe wall.

To read these pinning thermometers, it is necessary to access the decay pipe passageway during a down time, withdraw and disassemble the rods holding the pinning thermometers, and hand-read and record the temperatures. This has not proved to be easy, satisfactory, or informative.

It is proposed to install sufficient instrumentation to be able to read the temperatures in the radial holes with electronic devices accessed from the accelerator controls ACNET system, entering the data into the data-logging system.

The proposed methodology uses approximately 4 “RTD” devices in each of the six upstream-most of the ten available radial holes. At this time read-out cables have been pulled to the six upstream holes, and a PLC is installed in a controls rack in the target power supply support room. The necessary 24 RTDs have not been purchased, and the support system to hold the RTDs onto a rod to be slipped into the radial hole has not been designed, nor has a thermal insulation system to isolate the four RTDs per rod. A modest amount of mechanical engineering time is required, and some shop or mechanical tech time will be necessary to build and assemble the RTD rods and thermal isolation system. Some interconnect hardware to help read the data from each RTD into the existing PLC will also be required.

2.5.14 Radiological Concerns

Safety issues are an important consideration for Proton Plan 2. Fermilab is committed to maintaining a safe work place, minimizing worker exposure to radioactive material, and protecting the environment. Radiological concerns are of particular concern for the NuMI beamline given the intensity of protons directed on the target. The Proton Plan 2 upgrades will be installed during shutdowns occurring after the NuMI beamline has been operational for ~5 years. At this time residual radiation does rates in the target hall will be significant and advance preparations are necessary to perform the installation work safely and with exposure to radiation as low as reasonable possible.

Potential environmental impacts include radioactive air emissions, groundwater protection, prompt radiation doses, and tritium production. These issues are discussed in more detail in the following sections.

2.5.14.1 Proton Plan 2 Residual Dose Rates

The residual radiation field is that which remains after the beam has been shut down. In most situations at Fermilab the residual radiation field is almost exclusively gamma and beta rays. Residual dose rates are highest for longer irradiation times, shorter cool down times, and closer distances to the component of interest. Different materials cool down at different rates with concrete and aluminum, for instance, cooling down more rapidly then steel. Since steel cools down very slowly, it is typically the driving material for the residual dose rate for a given component or area of the Target Hall. The standard residual rate values quoted are for a 30-day irradiation and a 1 day cool down on contact, designated (30d, 1d). Thus we give values for (30d, 1d) at operations with 400 kW and 700 kW beam power (Proton Plan 2). For a given irradiation time and cool down time, values roughly scale with beam power. For components within the target chase, cool down times of 1 week are probably more realistic since it usually takes several days to access the chase.

Residual dose rates for Proton Plan 2 are best estimated by extrapolating from present NuMI measurements which correspond to approximately 170 kW beam. The simulation program MARS [83] can be used to determine the scaling factor needed to go from the measured numbers for a 170 kW beam to 400 kW and 700 kW beam.

There are three periods of interest for residual rates. We assume NuMI will take beam until the fall of 2009 and accumulate ~9E20 protons (perhaps up to 1.1E21) on the NuMI Target. At that point the first shutdown of Proton Plan 2 occurs and we will be upgrading components in the Target Chase and thus residual dose rates after this running period are of interest. The second time of interest is after running Proton Plan 2 at 400 kW for one year with the low energy target for MINERvA. At this point the medium energy target will be installed, Horn 1 most likely will be replaced and Horn 2 moved downstream. The third time is assumed to be after another year of running, but in this case at 700 kW. At this point one would perhaps need to replace a horn or work in the Target Hall for Proton Plan 2. For all these cases we use a combination of MARS runs and measurements to estimate residual levels.

2.5.14.1.1 Residual Rate Estimates for Proton Plan 2 Installation

Measurements of NuMI residual rates for some Target Hall components were taken during the March 2006 shutdown. For reference, Figure 58 shows components and shielding around horn 1. By March NuMI had taken 1.4E20 protons on target (POT) or an equivalent of 0.4 years of 4E20 POT/yr running. The scale factor from 0.4 years to 2.25 years (9E20 protons on target) of running for the steel and horn 1 endcap are approximately 1.5 based on cooling curves in reference [84]. Conservatively we can assume a factor of 2 higher residual rates for these components when we go to install Proton Plan 2 versus what was measured in the March 2006 shutdown.

March shutdown measurements taken after 3 days of cool down at three locations; (1) Horn 1, (2) Above the module near the ears (where shielding is light), and (3) On top of the T-blocks and gave rates of 80 R/hr, 200 mR/hr and 75mR/hr respectively (see Figure 58 and Table 20). MARS predictions for the horn are 160 R/hr and ~80 R/hr for the steel around it. Thus the measured and predicted rates for Horn 1 are considered consistent.

However, the value for the top T-blocks predictions [84] are closer to 4 mR/hr versus the 75 mR/hr measured. Thus values on top of the T-blocks (below the R-Blocks) are considerably higher than estimated by MARS. This is thought to be due to the thin shielding and the cracks in the “ears” of the module which was not precisely modeled in the MARS calculations. Extrapolating from these values one would expect about 1.5 times higher rates at the time of installation of Proton Plan 2 for these steel components. Thus the levels above the Horn 1 T-blocks could be as high as 300 mR/hr. To mitigate this, a platform will be built to cover the top of the T-blocks around the horn area after the R-blocks are removed remotely. This platform could be placed remotely and will be designed to reduce the radiation levels to a reasonable level for the amount of work that needs to occur in that area.

Another set of measurements was taken near the target on 4/8/06 after 6 weeks of cool down. Measurements at the bottom of the target module yielded levels of 50-150 mR/hr. Measurements near hottest spot on target (as close as one could reach) yielded levels up to 1.2R/hr at 2” from the target. The module, being of steel, should scale as the T-block values. Using reference [84], MARS values for the bottom of the T-blocks 30 day cooling curve, the value predicted by MARS (granted this is for the horn 1 module), is ~100R/hr on contact and scales to ~175R/hr after 2.25 years of running, or a factor of 1.75 higher. Thus one would expect these levels around the target module to increase to 100 to 300 mR/hr on contact (for a similar cool down time). The level of 1.2 R/hr near the target, if it was from steel components, might also scale by this factor. Target work replacement and horn replacement work is done remotely, thus these levels are not of great concern. Greater care will need to be taken when transporting radioactive components to the work cell and morgue, using temporary shielding for personnel as necessary.

Measurements on 3/20/06 after 3 weeks of cool down were taken of Horn 2 on contact at the downstream end and yielded levels of 5-8 R/hr. If these were due to steel activation, they would scale by the factor of 1.5. The horn, being aluminum, cools down rather quickly in a week and then one does not gain much after that, as shown in reference [84]. The aluminum would scale up by a factor of ~1.4 from present measurements to a similar cool down time when Proton Plan 2 components are installed.

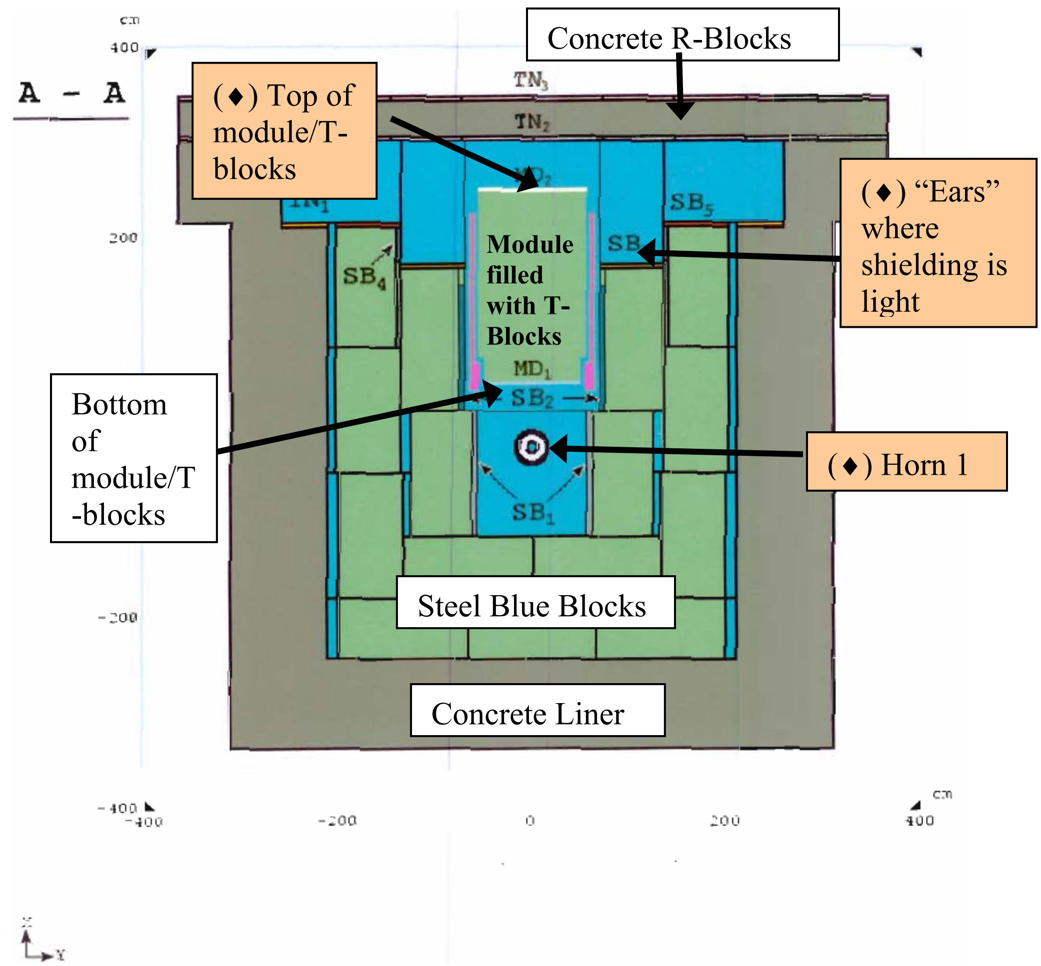


Figure 58: Cross Section of NuMI Target Hall, Component Region. As referred to in the text, the locations marked with (♦) are where the radiation dose rates were measured during the March 2006 shutdown.

2.5.14.1.2 Residual Rate Estimates for Proton Plan 2 Running

The first year of Proton Plan 2 running will be with the low energy target and the horns in the low energy (LE) configuration and at 400 kW. This running will be for the MINERvA experiment, which needs ~4E20 protons on target of low energy beam. The low energy target cannot withstand 700 kW, and thus this first year of LE running can be used to commission the accelerator complex for Proton Plan 2 running with the recycler as a proton pre-injector. Looking at the cooling curves in reference [84], one would expect rates only about 10% higher after another year of running. Thus the installation of components for Proton Plan 2 running in the shutdown following 2009 should be able to be handled in a manner similar to the 2009 shutdown. After the first year of running at 400 kW we will install the medium energy target and move Horn 2 to the medium energy position in preparation for running 700 kW beam for NOvA. The effect of moving Horn 2 to 20m downstream is not that large [84].

The increase for Proton Plan 2 (30d, 1d at 700 kW) versus NuMI (30d, 1d at 400 kW) is a scaling factor of between 1.4 and 3. The factor of 3 applies to the most downstream section of the chase, but more typically factors of around 2 are appropriate [84]. Scaling from the present numbers by using the scaling factor from (100d, 2d) to (30d, 1d) of 1.24, then one would expect values about 2.5 higher for (30d, 1d) on contact for Proton Plan 2 (700kW) versus present measurements.

Assuming 5 years of running at Proton Plan 2 levels and 1 day cool down, then there is another factor or 2.1 for steel or approximately 4 times higher then the present measured levels (for 5 years of Proton Plan 2 700kW running). If one assumes only one year of Proton Plan 2 running, then the factor is 1.9 instead of 2.1 and thus rates will be still in the range of 4 times higher for Proton Plan 2 after a year of running versus what is seen now for steel. This is after only a 1 day cool down. Table 20 summarizes the estimated residual dose rates for Proton Plan 2 under various scenarios.

Time	Protons on Target	Power (kW)	Scale Factor	Target (R/hr)	Target module/carrier (mrem/hr)	Horn 1 (R/hr)	Above Horn 1 Module, by "ears" (mrem'hr)	Horn 1 T-Blocks Top (mrem/hr)	Horn 2 (R/hr)
MARS predicted	1.40E+20	400				160	4	4	
Spring 2006 shutdown	1.40E+20	250	1	1.20	50 to 150	80	200	75	5 to 8
At time of first PP2 shutdown	9.00E+20	250-400	1.2 to 2	2.40	100 to 300	120	300	110	8 to 12
At time of second PP2 shutdown	1.20E+21	400	1.7	2.64	170	136	340	127.5	11.05
Running PP2 for a few years	6E20/yr	700	4	4.80	400	320	800	300	26

Table 20: Summary of Residual Dose Rate Predictions for Proton Plan 2 (PP2)

2.5.14.2 Ground Water Protection and Monitoring

2.5.14.2.1 Ground and Surface Water Activation

Water activation and contamination can occur when radionuclides produced in the soil or the rock surrounding an accelerator or beam line enclosure get into water passing through the soil or rock. Water activation also can occur when the beam produces radionuclides directly in the water contained in the soil or rock.

The NuMI beam is directed toward the MINOS Far Detector in Soudan, requiring an overall 3.34-degree downward slope. The pitch of the beamline causes it to traverse several different geological media, including the Silurian dolomite which is classified as a Class 1 groundwater aquifer. The transition between glacial till and dolomite, and thus the start of the groundwater aquifer, starts in the center of the lined section of the carrier tunnel, 55 to 70 feet below grade.

Operation of the NuMI beamline at Proton Plan 2 intensities will activate soil, rock and water in the vicinity of the beam tunnel. Most of the activation is within a few meters of the tunnel wall. The groundwater methodology [85] for NuMI involved estimating average inflow velocities, based on estimated inflow rates, tunnel geometry and grouting criteria. The beamline was divided into 12 regions, based on geometry and geology, in order to calculate groundwater velocities for each region. These velocities are used to estimate the resulting activation levels in the water flowing into the unlined sections of the tunnel. The estimates were compared to groundwater limits despite the fact that groundwater modeling shows that the NuMI tunnel captures all the water within the activation region and despite the fact that this water is pumped to the surface, out of necessity.

The section of the NuMI tunnel upstream of the Hobbit door (Door 2, NuMI Radiation Safety Drawings 9-6-7-4 C2) is lined with concrete, similar to other tunnel construction at FNAL. Downstream of the Hobbit door the tunnel is not lined. Groundwater modeling [86] of the subsurface hydrologic systems suggests that the NuMI tunnel functions like a well and captures nearby water, including the water from around the downstream lined section of the carrier tunnel. The water that flows into the tunnel is directed to the floor drains by wicking fabric or pipes. The wicking fabric lines the tunnel beneath the shotcrete in most beamline areas where dripping on components is a concern. Pipes are used in the decay tunnel, where shotcrete and wicking fabric is not present, except for in some upstream sections. Water flowing into the NuMI tunnel is pumped to the surface from the sump pump area at the base of the MINOS shaft. At the surface, the water is discharged to either the FNAL industrial cooling water (ICW) system or the pond at the MINOS service building.

2.5.14.2.2 Specifications

Allowable releases of various radionuclides to surface waters are documented in the FRCM as Derived Concentration Guides (DCGs). ^{22}Na and ^{3}H values of DCG's are presented in Table 21. Note that the groundwater value is based on United States Environmental Protection Agency (USEPA) 40 *CFR* 141[89].

	^{22}Na (pCi/ml)	^{3}H (pCi/ml)
Groundwater	0.4	20**
Surface Water	10	2000
* From DOE Order 5400.5 using the most conservative choices of GI tract absorption factor. ** From USEPA regulations 40 *CFR* 141.		

Table 21: DCGs* for Accelerator–produced Radionuclides in Water

The sum of the fractions of radionuclide contamination (relative to the values in Table 21) must be less than one for all radionuclides;

$$\sum_i \frac{C_i}{C_{reg\ i}} \leq 1$$

where the sum is over radionuclides, i, C_i is the concentration of radionuclide *i* in the water and $C_{reg\ i}$ is the concentration in Table 21.

The approved method for monitoring as to whether one is within the limits is by monitoring wells for groundwater and surface sampling for surface waters. Verification that such limits are not violated is accomplished during the facility operation through the Lab-wide monitoring program.

2.5.14.2.3 Results

The NuMI Tunnel enters the groundwater aquifer starting at about the Hobbit door. The NuMI tunnel portions upstream of the Hobbit door are lined with concrete; downstream of the Hobbit door the NuMI tunnel is located in rock (dolomite). The water naturally flows down the floor drains and into the sump at the base of the MINOS shaft, where it is pumped to the surface. This includes the water along the lined section of the carrier tunnel, which is captured by the unlined section of the carrier tunnel. During the operation, NuMI beam line losses are monitored and minimized to keep water activation and residual dose rates in the tunnel below limits defined in the FRCM.

The beam permit system helps prevent repetitive beam losses by looking at the quality of the MI beam, losses on the last extracted pulse and readiness of the NuMI beamline. These two systems make it extremely unlikely that beam loss at the level of 1 part in 10^{+5} will occur for more than a couple pulses. A monitoring well (S-1273) down gradient of the carrier tunnel region is sampled periodically in accordance with reference [90]. The sumps for the NuMI beamline are sampled periodically in accordance with the Routine Monitoring Program procedure ADDP-SH-1003 [91].

The Proton Plan 2 target, two horns, decay pipe and the hadron absorber are cooled by water. The water in these cooling systems will become activated due to exposure to the radiation. The most significant radioisotopes, from a contaminant aspect are ^3H, and to a lesser extent ^7Be, because of their rather long half lives (many days or years instead of minutes). The FRCM provides suggested guidance for replacing the water in RAW cooling systems when the tritium concentrations reach 6.7E+5 pCi/ml. Routine analysis of the RAW system concentration levels, the neutrino program schedule, operational impact to other parts of the accelerator complex, and ALARA principles will all be considered when determining the appropriate timing of water replacement. The water in most Proton Plan 2 RAW systems should not need to be changed annually based on the FRCM guidance levels for tritium. The extremely unlikely catastrophic loss of the RAW from any of the Proton Plan 2 cooling systems does not cause any significant increase to the concentration of radionuclides in the discharge to the surface waters [92] and results, conservatively, in a release of water at 7.8% of the surface discharge limit. The controls, interlocks and alarms designed for these systems prevent any catastrophic losses and damage to the equipment as well (Section 4.7.4 of [49]).

Measurements at the NuMI well show no detectable tritium (<0.1 pCi/ml) after 1.4E20 protons on the NuMI Target. For Proton Plan 2 running, we assume 6E21 protons on target or 30 times as much integrated beam (See Section 4, "Proton Projections"). For a worst-case scenario we assume the tritium levels scale with integrated beam instead of instantaneous beam intensity. If all tritium leached out of the rock as the water flowed into the NuMI tunnel, one would expect the tritium levels to scale with instantaneous beam intensity instead of integrated intensity. There is some indication that not all the tritium leaches and thus we will (super) conservatively scale with integrated protons on target.

Table 22 shows the regulatory limits, measured values and some projections for tritium and ^{22}Na levels in NuMI sump (surface water) and the NuMI well (groundwater). The last column shows the predicted concentrations of tritium and ^{22}Na after six years of operation with 10E20 protons per year. In reality, the sum of the tritium and ^{22}Na relative to the limits must be less then one, as in the equation shown previously in this section. To reach the groundwater limit in the monitoring well, scaling from the null measurement of 0.1 pCi/ml, SNuMI would need to run 9 years, based on a total of 9E21 protons on target. For the sump, where the limits are 25 to 100 times higher than for the groundwater (monitoring well), SNuMI could run over 100 years at 6E20 protons/yr. For ^{22}Na where our level of detection is not low enough for us to extrapolate without going over the limit, predictions are more difficult. We are currently perusing more accurate measurements in both the well and the sump. Clearly if less than 0.03 pCi/ml are typically measured in the sump for ^{22}Na, then the monitoring well will have significantly less. In reality, the likelihood of any water from the large NuMI tunnel making it away from the tunnel is extremely small. If any did reach the monitoring well, if would be so diluted with other water, it would likely not be measurable. Further measurements of ^{22}Na and tritium in the near future will be used to update these projections, along with graphs of measurements of these values versus integrated POT.

	Regulatory Limits (pCi/ml)		Measured (pCi/ml)		Limit for six years (pCi/ml)	
	GW	SW	GW	Sump	GW	Sump
^{3}H	20	2000	< 0.1	6	< 1	52
^{22}Na	0.4	10	< 0.01	< 0.03	< 0.3	<0.8
Integrated protons on target			1.40E+20		6.00E+21	PoT/6yr

Table 22: Regulatory Limits, Measurements and Projections for Tritium and ^{22}Na. With the exception of ^{3}H in the NuMI sump water, all measured values were below detectable limits. Values quoted as less than were below detectable limits. Therefore scaling of these concentrations to higher beam power can only provide upper limits.

2.5.14.3 Radioactive Air Emissions

The total tritium and non-tritium radioisotopes air emissions from NuMI areas, under current configuration are estimated for the Proton Plan 2 operations. Estimates are based on measurements, except for SR3 where a conservative estimate has been used. The current NuMI design intensity is 0.4MW, and Proton Plan 2 experiment is assumed to run 0.7 MW of beam power.

2.5.14.3.1 Non-tritium isotopes emitted from the stacks

Usually ^{15}O (122.2 sec.), ^{13}N (10min), ^{11}C (20min), ^{41}Ar (1.8hrs) and some times ^{38}Cl (37.2min) and ^{39}Cl (55.5min) are detected at the stacks. Because of relatively long transit times from the production point to the stack (20min to hours) shorter-lived isotopes are not observed. Since the transit time through SR3 is only 2.4 seconds short-lived isotopes can reach the release point and the SR3 stack air monitor. Because of the short transit time from the NuMI target hall to the release point of SR3, the isotopes ^{14}O (71 sec), ^{19}O (27.1 sec) and ^{40}Cl (1.4min), will be able to reach the end of the stack on the surface. Assuming, conservatively, that these short-lived isotopes are produced with the same cross section as the more common species, the ratios of short-lived to the longer-lived isotopes at the site boundary can be estimated. The results show that $^{14}O/^{15}O$ fraction is about 14%, $^{19}O/^{15}O$ is 4 orders of magnitude smaller and $^{40}Cl/^{38}Cl$ is about 2%. Note that ^{13}N and ^{11}C are usually 90% of the total release at the stack point. All the other isotopes are less than 10%. Therefore, fractions of 10% will not affect the site boundary dose significantly. Table shows the total activity release from the NuMI stacks at 400 kW and 700 kW, extrapolated from measurements. A release of 73 Curies of radionuclides corresponds to an annual dose equivalent of 32 micro-rems at the Fermilab site boundary.

	Measurements (Scaled to 400 kW) Ci/yr	Proton Plan 2 (Scaled to 700 kW) Ci/yr
EAV1	5.6	9.8
EAV2	17.1	30.0
EAV3	11.5	20.1
SR3 (est.)	7.5	13.1
Total (Ci/yr)	**41.7**	**73.0**

Table 23: Radioactive air emissions estimates from the stacks.

2.5.14.3.2 Tritium Release

In October 2005 during the periods that NuMI experiment was operating at 200 kW, and before the installation of the Target Hall dehumidification system and the removal chiller condensate from the inflow, all of the tritium ended up in the holding tank. The maximum tank concentration observed was at this time was 27 pCi/ml. The water inflow rate was 177 gallons per minute. This corresponds to about 9.5 Curies of tritium per year. Assuming, conservatively, that all of this tritium is released to the air, at Proton Plan 2 beam power of 700 kW, this will corresponds to about 33 Curies of tritium in a year. This release will contribute about 0.2 micro-rems /year to the site boundary dose.

Conservative estimates of the total radioactive air emissions due Proton Plan 2 operation demonstrate that no revisions are required to the laboratory's permits or monitoring methodologies.

2.5.14.4 Prompt Radiation

There are several labyrinths and penetrations in the NuMI tunnels and halls for personnel access, connection to equipment, air inlets and exhausts, survey risers and an air-cooling labyrinth. Prompt radiation from the penetrations and labyrinths are estimated by calculations and extrapolation from measurements during the operation of NuMI. The results of the radiation attenuation calculations for these labyrinths and penetrations are given in the Table 24 and the discussed below. Dose rates due to losses under normal and accident conditions are given. An accident is defined by five sequential full intensity proton pulses. Normal losses depend on the location. Near the target and baffles it is full beam loss during an hour and 0.01% of the full beam at other locations.

Region	Normal Loss		Accidental Loss	
	Exit Dose Rate		Exit Dose Rate	
	(mrem/hr)	Comment	(mrem/hr)	Comment
Survey Riser SR-1	6	existing plug is ok	158	existing plug is enough
Air Vent EAV-1	< 0.001	OK (loss rate 1E-4)	< 0.001	OK
Survey Riser SR-2	0.37	existing plug is ok	9.7	existing plug and posting
Target Hall labyrinth	0.007	OK	0.17	OK
Target Hall Equipment Door	1.3	Post as Controlled Area Min. Occup.		
Stripline Penetration	239	Existing shielding ok	Current shielding is sufficient	
RAW Penetration	0.11	Pipes will fill voids		
Survey Riser SR-3	0.006	OK		
Vent EAV-2	0.002	OK		
Vent EAV-3	0.001	OK		
Absorber Labyrinth	0.9	Post as Controlled Area Min. Occup.		
Muon Alcove 2	0.32	Door posted and interlocked		
Muon Alcove 3	0.02	Door posted and interlocked		
Muon Alcove 4	<0.001	Door posted and interlocked		

Table 24: Dose rates at the exit and mitigation where needed for the NuMI labyrinths and penetrations.

2.5.14.4.1 Survey Risers 1, 2 and 3

The accident dose rate at the exit of SR-1 is 158 mrem/hr. The existing plug, which is combined 3 ft. iron and 1 ft. concrete, will reduce the accident dose rate to 56 micro-rem/hr. This reduced dose rate does not require any radiological postings. The plug will also reduce the dose rate due to normal losses to the same classification.

SR-2 plug is a combined 2 ft. iron and 1 ft. concrete. The plug will reduce the exit dose rate from normal beam losses to below 1 micro-rem/hr. The accident rate is 9.7 mrem/hr which requires radiological posting. There is no credible accident case that can produce losses under the SR-3 opening which are larger than the assumed normal losses.

2.5.14.4.2 Air Exhaust stacks EAV-1, EAV-2 and EAV-3

The dose rates at the exit of EAV-1 are insignificant both under the accident conditions and normal loss rates. For EAV-2 and EAV-3 the source term calculated with MARS is due to the interaction of the full beam with the target. Based on the combined dose rates from EAV-2 and EAV-3, the areas around these stacks do not need to be posted. However, because of the possibility of significant radioactive air emissions from these three stacks the area around them will be posted as Controlled Area.

2.5.14.4.3 Target Hall Labyrinth

In addition to radiation propagating through the legs of this labyrinth there is a significant contribution to the radiation field in the second leg due to leakage through the wall (the so called short circuit). This leakage dose rate is calculated as an additional source term. The resulting dose at the exit is added to that originated at the entrance to the first leg. The dose rates under both the normal and accident conditions are low enough that the exit of this labyrinth requires no posting.

2.5.14.4.4 Target Hall Equipment Door

Target hall is not accessible during the beam operations. There is a 10 ft. concrete door blocking the direct access to the hall. Based on the MARS source term behind the door and attenuation of the concrete, the dose rate immediately outside the door is 1.3 mrem/hr. The classification for this area would be Controlled Area with limited occupancy. Given the location of this area, it is naturally a limited occupancy area.

2.5.14.4.5 Horn Strip-line Penetration

The section of the penetration between the horn and the top of the module is not considered here, since the target hall is not accessible during the beam operation. Only the section of penetration between the target hall and the power supply room is needed to calculate the dose to personnel in the power supply room. The source term is calculated at the entrance to this penetration using MARS. The penetration is modeled as empty, but it is partially filled with the strip-line, which material occupies about 10% of the cross sectional area. The neutron spectrum at the entrance to this penetration is mainly composed of neutrons of energy less than 1 MeV. Polyethylene is an effective absorber of these neutrons. Since the rest of the penetration cannot be filled completely, polyethylene sheets have been used near the entrance and exit of this penetration to shadow the penetration to effectively reduce the dose rates. The dose rate at 200 kW for the unshielded penetration was expected to be 68 mrem/hr. The chipmunk detector near the shielded penetration have been consistently been detecting only the background radiation. The calculated dose rate for the 700 kW case (Proton Plan 2) is less than 0.05 mrem/hr.

2.5.14.4.6 RAW Systems Penetration

MARS calculations provided the source term at the entrance to this penetration. Similar to the horn strip-line, the section of penetration between the target hall and the RAW room is used to calculate the dose to personnel in the RAW room. This penetration is 95% filled with RAW pipes filled with water, which reduces the amount of radiation leakage greatly. Water is a much more effective shield against low energy neutrons than concrete. As Table 24 shows, the dose rate from the filled penetration is small. The RAW room is not accessible during the beam operations.

2.5.14.4.7 Hadron Absorber Access Labyrinth

Figure 59 shows the layout of this labyrinth. Access to the hadron absorber area is controlled at the fire door the dose rates are calculated at the door. Some of the concrete bricks used on top of the blocks or along the walls have a density of 1.44 g-cm^2. To check the effects of this lower density, the calculation was done assuming the whole labyrinth is constructed with the lower density concrete. In addition to the labyrinth, there are two possible short circuit paths; through the 6 ft. concrete section and the 9 ft. section. The leakages through these two pathways are added to the dose from the labyrinth. The resulting dose rate is 0.9 mrem/hr. Combined with the dose rate from the shielded RAW system skid near the exit will require that this section of the bypass tunnel to be posted as a minimal occupancy Controlled Area.

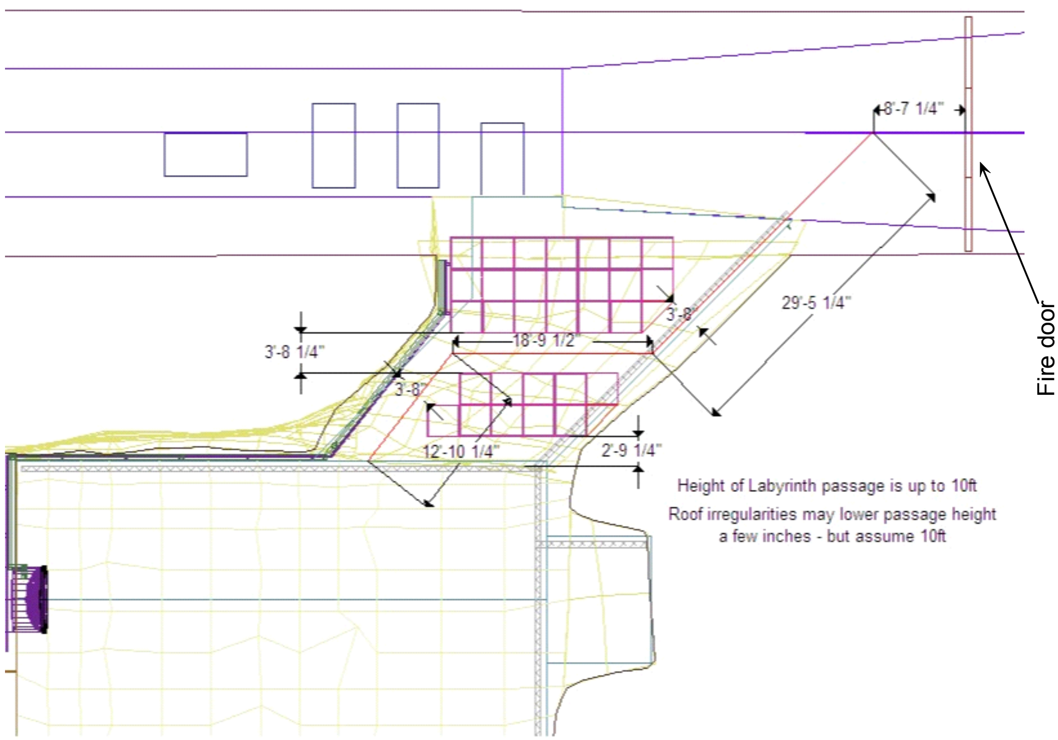


Figure 59: Schematic drawing of the hadron absorber, access labyrinth and the bypass tunnel.

2.5.14.4.8 Beam-on Dose Rate at the Gate to the Muon-Alcoves 2, 3 and 4

The 400 kW source terms for the NuMI muon-alcoves are given in [87]. Alcoves 2, 3 and 4 have no direct opening (first leg) to the source of radiation. Therefore, the transport calculations used are those for second and further legs. Figure 60 shows an example of a two-leg approximation to a curved alcove. The angle between the two legs is the angle of curvature of the alcove as given on the drawings.

Most of the muons are in a forward going cone. Being weakly interacting and relatively high energy very few of the muons entering the alcove will scatter at large angles to reach the alcove gate. The insignificant contribution of the muons to the dose rates at the alcove gates are ignored in these calculations. The fluence-to-dose conversion factor for neutrons behind a thick soil shield from FRCM Table 8-3 is used. The results of calculations for 700 kW are given in Table 24. The area near alcove-2 gate will be posted as Controlled Area, minimal occupancy.

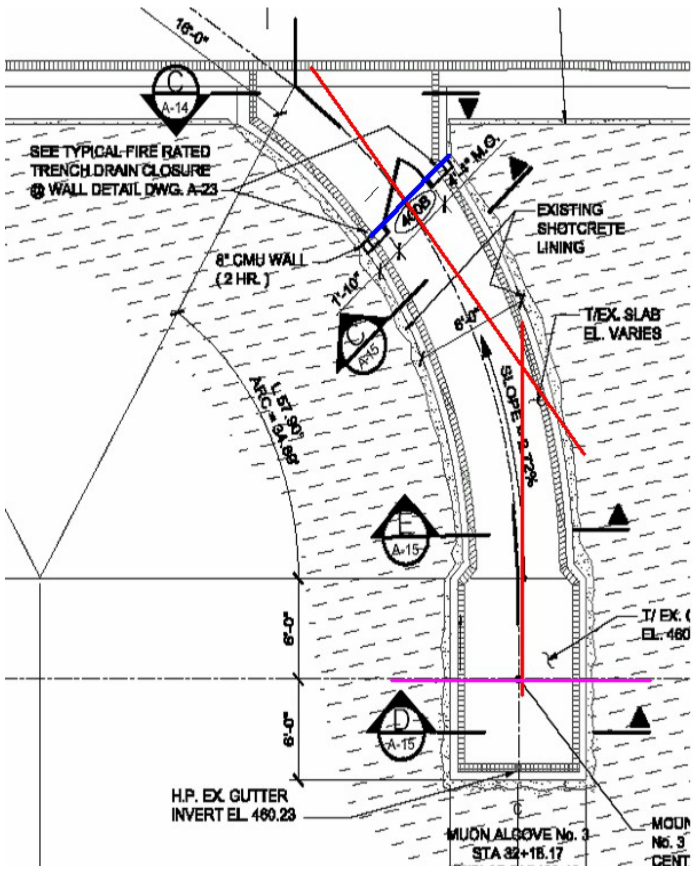


Figure 60: An example of a two-leg approximation to a curved labyrinth. The red lines show the straight leg approximation. Leg 1 started at center of the alcove to where it crosses the second leg (red line). Leg 2 is defined from the intersection to the gate of the alcove.

2.5.14.4.9 Door of the RAW room

The NuMI RAW room is where the primary water-cooling systems for the horns, target and the decay pipe are located. The cooling water used for these devices becomes activated, hence the name Radio-Active Water (RAW). The dose rate at the door is due to the radiation leaking through the concrete wall, through the gaps between the top of the walls and the rock ceiling and through the RAW room doorway. Table 25 gives the radioactivity concentrations in the tanks after one year of operation at Proton Plan 2 beam power. The resulting dose rate at the door due to each one of the systems is given in

Table 23. About 90% of this dose is from the opening between the top of the walls and the rock ceiling.

RAW Source	Horn1	Horn2	Target	Decay Pipe	**Total**
Tank activity (Bq/ml)	1.16E+07	3.43E+06	4.32E+06	5.74E+03	**(mrem/hr)**
Dose rate at door	1.34E+00	3.67E-01	1.49E-01	1.94E-03	**1.9**

Table 25: Activity concentrations of various RAW systems after one year of Proton Plan 2 operation and the expected dose rate at the door of the RAW room.

The total dose rate of 1.9 mrem/hr is a conservative estimate based on one-year full intensity operation without any time to cool down. No credit is taken for the shielding due to all the pipes, I-beams and other equipment. Most of ^{7}Be will be trapped in the DI-bottles and filters, which are locally shielded. Seventy percent of the activity is due to the isotope ^{15}O, which has a 2-minute half-life. A 2-minute transit time from the target hall to the tank can reduce the above rates by 30%. Based on the above assumptions and results the dose rate at the door, the area outside the door should be posted as Controlled Area with Minimal Occupancy classification.

2.5.14.4.10 Target Hall Air Cooling Labyrinth

The exit of this labyrinth is in the target hall and is not accessible during the beam operations.

2.5.14.4.11 MINOS Access Shaft and EAV-4

The dose rates at the base of the MINOS access shaft and in the MINOS hall are negligible. No measurable radiation dose rate due to the Proton Plan 2 beam operations is expected at the top of the MINOS access shaft or the EAV-4.

2.5.14.5 Maintenance and Repair

The original NuMI Target Hall Work Cell and associated Radioactive Component Removal Plan were developed with 2 key concepts in mind. The first was that components (Target/Baffle, Horn 1 & Horn 2) would not be repaired in the Work Cell, but only replaced. The second was that failed, radioactive components would be stored long term in a shielded pit, called “the Morgue” with no plans for radioactive component removal up-shaft for disposal. Practical lessons learned from 1-1/2 years of operational experience of NuMI and the proposed upgrades for Proton Plan 2 have altered those fundamental concepts and require re-designing the Work Cell and Radioactive Component Removal Plan.

2.5.14.6 Work Cell Upgrade

The current Work Cell has minimal capability to perform repair activities on radioactive components. It consists of three permanent shield walls and a steel shutter (or sliding door) on the fourth side (see Figure 61, Figure 62, and Figure 63). Two of the shield walls are outfitted with lead glass windows consisting of lead glass blocks. On top of the shield walls is mounted an accessible deck which contains the module mount features required to interface with the component modules. Thus component modules removed from the chase are moved by crane into the Work Cell and hung from the top of the shield wall deck. A lift table assembly in the bottom of the Work Cell allows components to be removed from and installed to the bottom of the modules with workers working from above the deck [88].

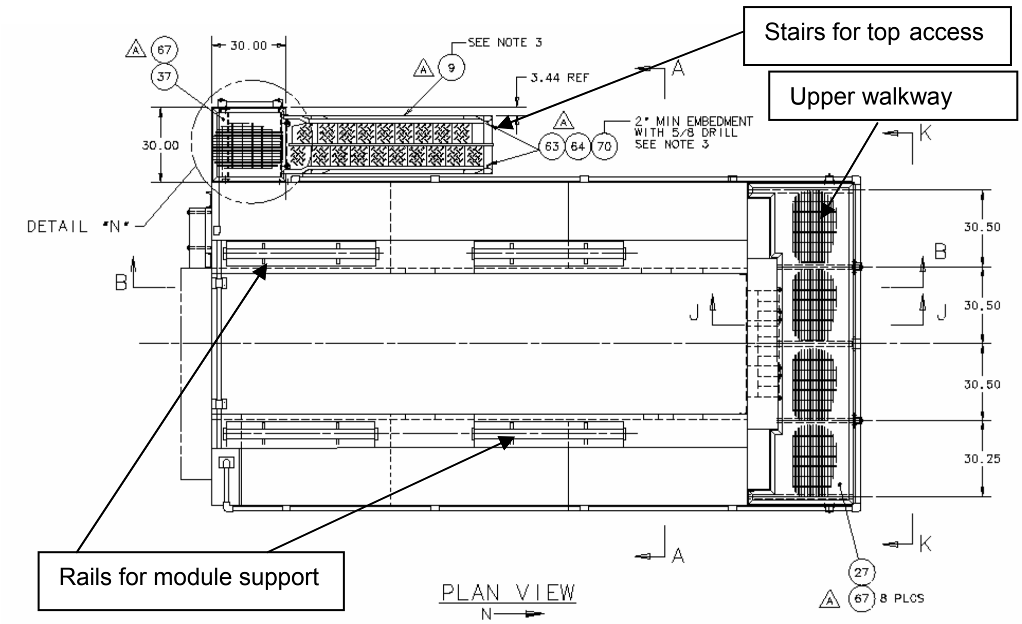


Figure 61: Plan view of existing Work Cell.

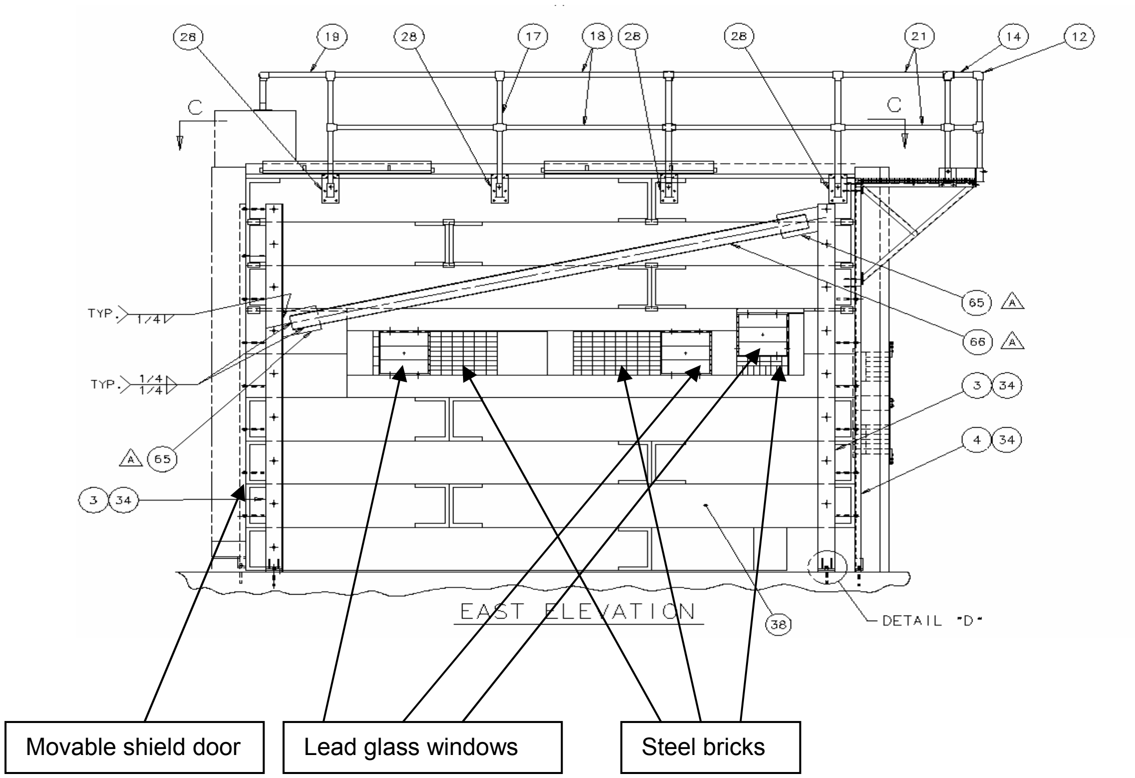


Figure 62: East Elevation view of existing Work Cell.

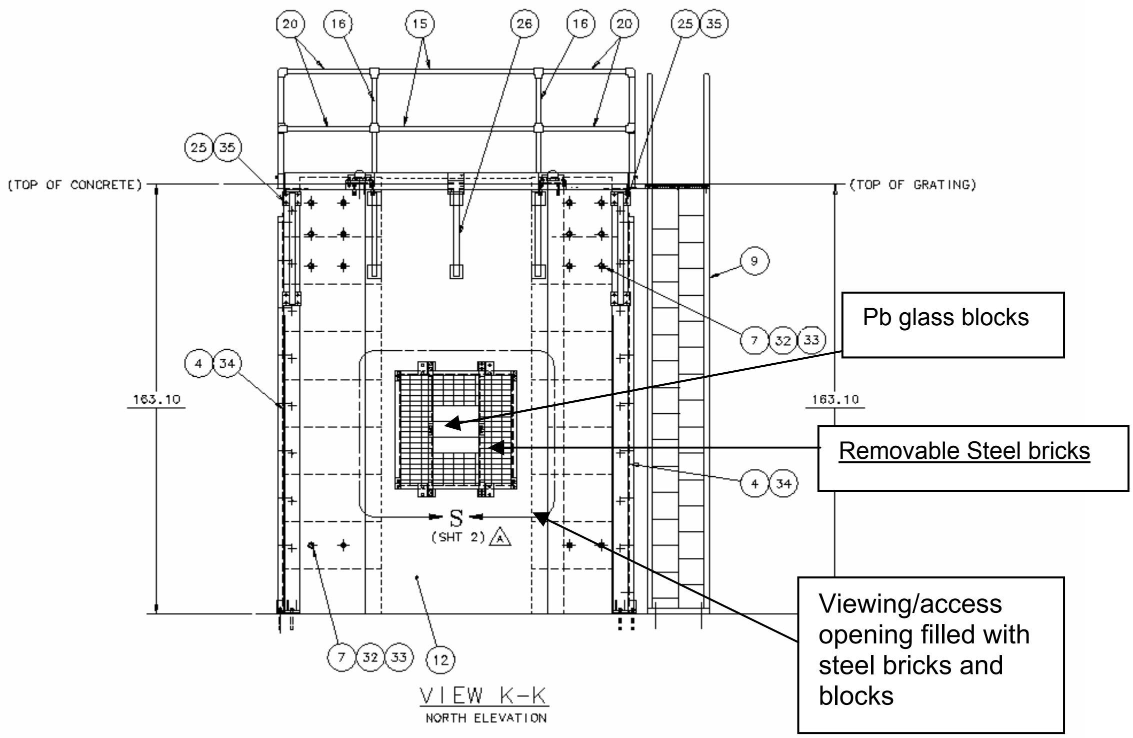
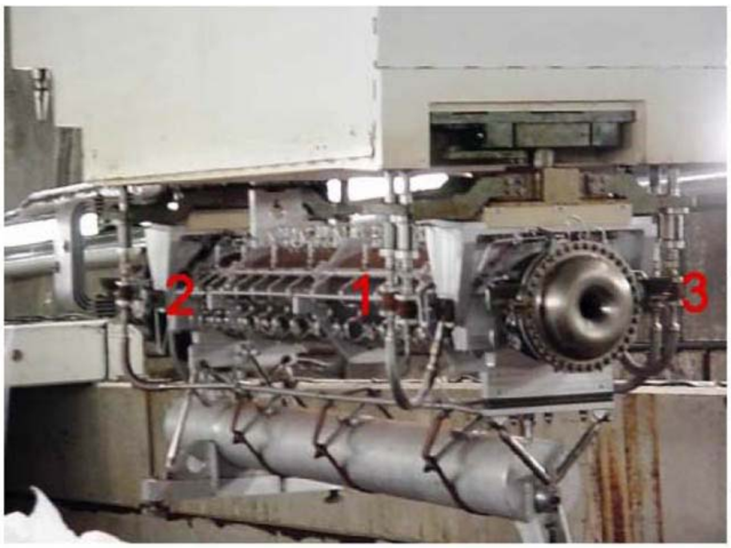


Figure 63: North Elevation view of existing Work Cell

Since commissioning the NuMI Target Hall in early spring of 2005, repair activities utilizing the Work Cell area have included: Target Water Leak repair, Horn 2 ground fault repair, Horn 2 ceramic water line insulator replacement, and Horn 1 ceramic water line insulator replacement. Due to this history (primarily driven by the long lead time to construct spare components and the cost of spare components), it is clear that repair of radioactive components will be part of normal operations rather than changing out the entire failed component. Dose rates of components repaired thus far have ranged from a few R/hr to 40 R/hr at 1 foot (see Figure 64). Predicted maximum dose rates are 300 to 400 R/hr at 1 foot for the Proton Plan 2 components at 700 kW. (See Section 2.5.14.1.2, Residual Rate Estimates for Proton Plan 2 Running).



Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	35000	75000
2	40000	75000
3	35000	80000

Figure 64: Horn 1 residual dose rate survey results during ceramic water line insulator replacement.

During most of the above-mentioned repairs, temporary shielding was erected just outside the Work Cell shutter. The component to be repaired, still hanging from its module, was partially moved out of the Work Cell proper using the crane. The temporary shielding was fashioned to allow workers to approach the repair area on the failed component and perform repair tasks (see Figure 65). Although this method worked, it took a long time to plan, fabricate and execute the repairs. In addition, repair activities had to be split into several shorter sub-tasks in order to keep dose to any individual worker to an acceptable level (for the Horn 1 water line ceramic insulator replacement, over 16 technicians were used to execute tasks lasting from 6 to 12 seconds each).

The design concept for the Work Cell upgrade is to design and fabricate a (possibly reconfigurable) set of shielding walls that can be assembled to form a shielding extension to the current Work Cell. The Work Cell upgrade will include at least one set of tele-manipulators (such as the set shown in Figure 66) and lead glass window unit to allow remote repair activities without excessive dose to workers. If space constraints do not allow the shielding extension to remain in an erected configuration, then the shielding extension and tele-manipulator station will need to be designed for easy erection and disassembly to keep access times for repairs short. It may also need to be designed to allow storage in the limited space of the Target Hall when not in use. Thus it is envisioned that a modular design will be pursued such that the shielding extension can be custom configured to place the manipulators at the proper location for the repair work at hand while providing adequate shielding for workers.

Figure 65: Temporary shielding installed outside of existing Work Cell prior to Horn 1 ceramic water line insulator replacement.

Detailed estimations of shielding requirements for the Work Cell upgrade have not yet been completed. Preliminary results indicate that about 9 inches of steel or 18 inches of lead glass are required to reduce the highest component dose rates (400 R/hr) to around 2 mrem/hr where workers would be stationed. Also of note is that the existing work cell shielding is predicted to be adequate for the Proton Plan 2 components, keeping dose rates at the shielding periphery (on contact with shielding surface) less than 10 mrem/hr.

Currently available commercial tele-manipulator designs utilize an overhead pass through tube that may interfere with component modules during repair activities. Therefore at this stage the Work Cell upgrade requires components to be removed from their modules during repair activities requiring the tele-manipulator station. This scenario requires a remotely positioned worktable to hold the components for repair in the Work Cell extension. It is planned to investigate other tele-manipulator solutions which will enable working on components while they are still attached to their modules.

In addition to the tele-manipulator station, adjustable video cameras and mounts will be needed to provide workers with a functional view of the repair activities. These cameras and mounts will be placed and adjusted specifically for the repair activity at hand.

Remote adjustment of the cameras is desired so that the viewpoint may be altered without entering the Work Cell extension.

Obviously, radioactive contamination issues must be addressed at an early stage and features of the Work Cell extension will be designed to appropriately handle the predicted levels of contamination. Liners, dust covers, bellows and high-efficiency particulate-filtered vacuums may become part of the design as necessary.

Aside from designing and building the Work Cell extension, modifications to the designs of the components will be necessary to accommodate the tele-manipulator jaws and tongs for anticipated repair activities. A remote repair tool-set will need to be designed and fabricated to facilitate interactions between component features and the manipulators. Also spare parts and tools to repair the tele-manipulators themselves must be stocked to ensure efficient repairs.

Training of tele-manipulator operators and trouble-shooting of the Work Cell extension will take place above ground before installing it in the Target Hall. The Work Cell extension will be erected in various configurations and mock repairs will be conducted in order to identify and solve conflicts and problems. It is desired that repair and maintenance of the tele-manipulators occur upstairs so that interference with beam-on operations of the Target Hall is minimized. This will require designs that allow for easy removal/insertion of the tele-manipulators and provisions for decontamination and/or contamination containment

Figure 66: Heavy duty through wall tele-manipulator (courtesy Central Research Laboratory).

2.5.14.7 Radioactive Component Removal Plan

The original NuMI Target Hall Radioactive Component Removal Plan was simply to store failed components (Horns, Target/Baffle) in a shielded vault or pit area called the

Morgue. The Morgue sits just upstream of the Target Chase and has a floor space of roughly 26 feet by 7 feet and a depth of 10 feet (see Figure 67). It was planned to be able to store 8 components in the Morgue. However, recent experiences have indicated that it may be difficult to achieve this in practice (for instance, the Target/Baffle Carrier that was just replaced had the Target stuck in an extended position such that its total length was much greater than anticipated). Thus Morgue capacity is realistically limited to about 4-5 components total. In order to do this, the radioactive components must be stacked on top of one another using an as of yet un-designed shelving system. Due to the high residual dose of radioactive components, placement of the components in the Morgue is done remotely using the Target Hall crane and specially designed lifting fixtures.

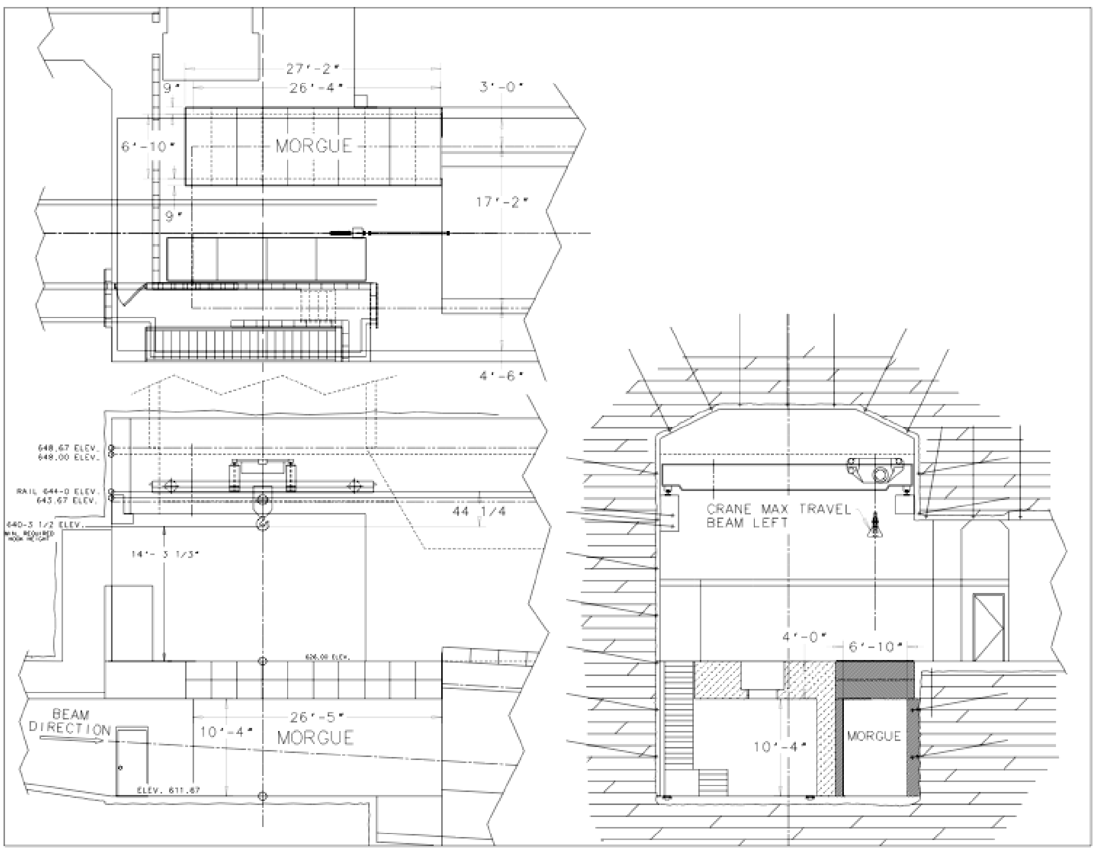


Figure 67: Plan and elevation views of existing Morgue area.

With operations at the NuMI Target Hall for Proton Plan 2 now projected to extend beyond 2011, capacity of the Morgue is inadequate for storage of radioactive components. It is conceivable that Proton Plan 2 components could require storage at a rate of 2 components per year, on average. In addition, component modules, previously not considered replaceable, may need to be replaced during the Proton Plan 2 era. The Radioactive Component Removal Plan must be developed to include short-term storage of components and possibly modules in the Morgue, removal of those components up-shaft, and subsequent long-term storage.

Short-term storage of components in the Morgue is currently not efficient due to the lack of a remotely assembled shelving system. Currently there is 1 failed Target/Baffle Carrier assembly in the Morgue (see Figure 68). Due to the lack of crane coverage to the extreme beam left edge of the Morgue pit, placement of the Target is not ideal for placing additional components next to it. And obviously it is not possible to place another component on top of the Target without some sort of support platform. In order to maximize efficiency of the Morgue, it is planned to design a Morgue shelving system that accepts components from the crane and remotely places them in storage locations. It is desirable to design this shelving system to accommodate the "first-in, first-out" nature of short-term storage so that components that have been stored in the Morgue the longest can be removed from the Morgue without having to handle more recent (and higher dose rate) additions.

Figure 68: NuMI Target 1 in Morgue showing limits of crane travel to beam left.

Short-term storage of component modules in the Morgue is more difficult to achieve. A module consists of 2 end blocks (upstream and downstream) through which penetrations exist for cooling pipes, remote positioning shafts, and instrumentation. The end blocks are connected to each other via welded side plates. In between the end blocks is space for the "T-blocks" shielding steel, which are removed prior to lifting the module (see Figure 69). The sizes and weights of the modules are much greater than that of the components. Although it is possible to fit a module in the Morgue currently, it does not leave much room for other radioactive components. In addition, the weight of a module currently pushes the limit of the MI-65 shaft crane capability (30 ton) and does not leave much room for a shielding coffin to handle radioactive modules during removal up-shaft. Since a large portion of the modules is empty space (between end blocks), volume reduction methods will be investigated to separate a radioactive module into more easily handled sizes if storage in the Morgue and/or shielding coffins are required. These volume reduction methods will require serious research and development by mechanical and radiological engineers including prototyping. Certainly any new module design will investigate incorporating features to allow disassembly into smaller portions.

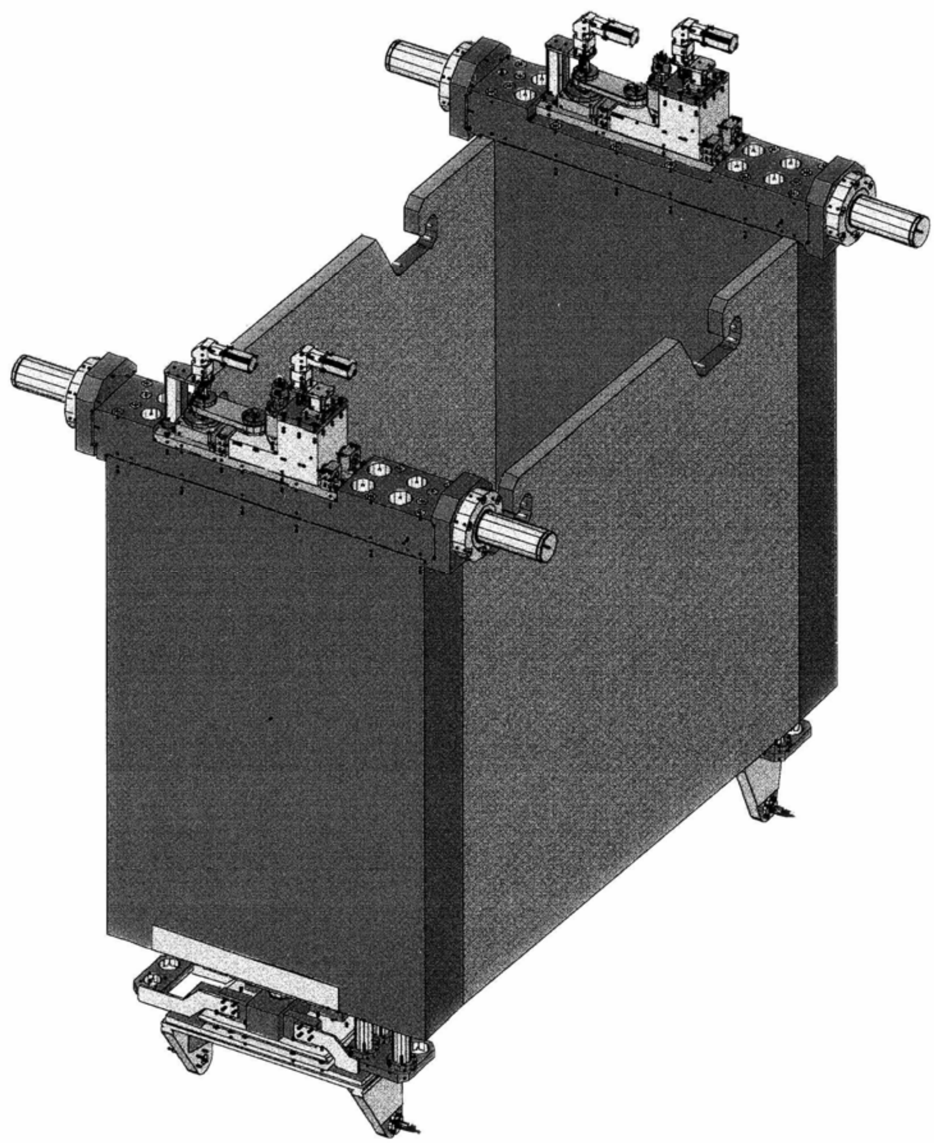


Figure 69: Isometric view of Target/Carrier Module without T-blocks.

Removal of radioactive components up-shaft can be achieved by constructing customized steel shielding coffins for each component. A transport cart will also be needed to move the radioactive components (preferably loaded in their coffins) from the Morgue area to the base of the MI-65 shaft (see Figure 70). If the needed coffins are either too heavy for the shaft crane (30 ton) or too unwieldy for the transport cart, the components could be removed up-shaft without coffins (or with inner/outer coffins as was done with MiniBooNE). Lightweight containers to minimize contamination could be used. Obviously, in the case of no coffins, motion of the transport cart and the crane-lift up-shaft must be done remotely, probably with temporary shielding walls constructed both at the base of the shaft and at the top of the shaft.

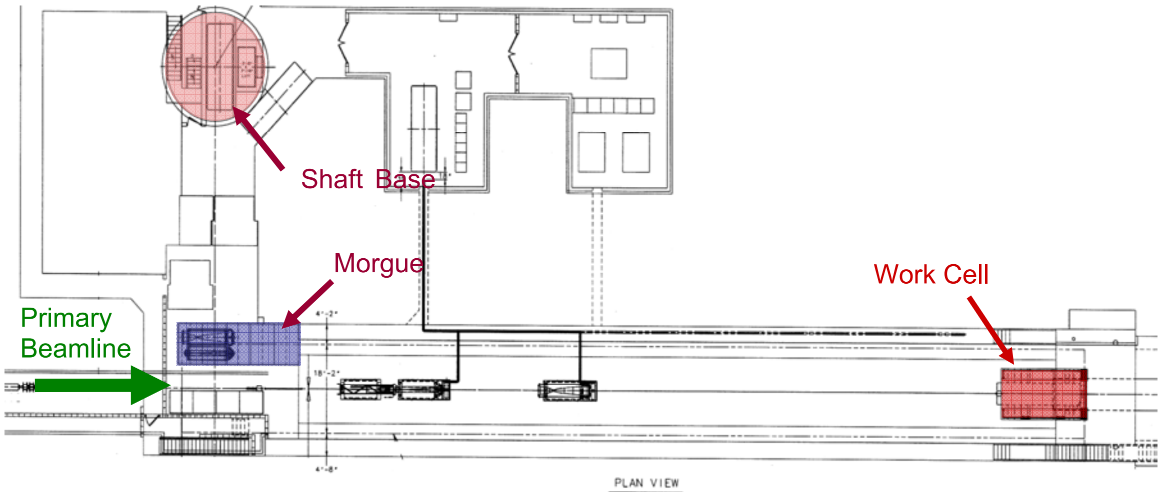


Figure 70: Plan view of Target Hall showing relative locations of Morgue, Work Cell, and MI-65 shaft base.

Once a radioactive component (in coffin) is upstairs at MI-65, it can be placed on a suitable trailer for transport to long-term storage. Currently long-term storage is considered to be located at Target Service Building (TSB). TSB is a long enclosure surrounded by earthen berm and is equipped with a train car system (80 ton capacity each car) for storage of radioactive components. Currently items stored at TSB include P-bar Target Hall components and 1 MiniBooNE horn/target assembly (see Figure 71). In fact, the procedure for radioactive horn/target removal for MiniBooNE will be used as a model for the Radioactive Component Removal Plans. The crane at TSB is limited to 20 tons. It may be necessary to divide the total coffin weight into an inner and outer coffin assembly in order to facilitate off-loading at TSB (as was done with MiniBooNE).

Detailed estimates of shielding requirements for removal coffins have not been performed yet. Rough estimates indicate that 6 inches of steel will attenuate the highest dose rate (Horn 1) of approximately 400 R/hr to less than 100 mrem/hr at 1 foot from the coffin surface. Due to the large outer dimensions of the Horn assemblies, coffin wall thicknesses in this range (6 inch) may push the limits of the shaft crane capacity. Volume reduction methods will be investigated to reduce the size of required coffins. For instance, the actual Target and Baffle devices are much smaller yet have a much higher dose rate than the Carrier structure that they mount to. Disassembly of these items from the Carrier would drastically reduce the size and weight of a Target coffin. Similarly, disassembly of the water collection tank and downstream stripline from a Horn 1 assembly could reduce the size of a Horn 1 coffin by a factor of 4 or more. Obviously any features needed to facilitate disassembly would have to be incorporated into new Horn and Target design as well as tele-manipulator tool set and Work Cell Upgrade designs.

Figure 71: Interior picture of TSB showing P-bar Target Hall coffins in storage on train cars.

Removal of component modules can be handled in a similar manner except that, if dismantling a module is not possible, the sheer size and weight of a module would preclude the use of coffins for shielding during transport. In that case, temporary shielding and remote viewing equipment may have to be installed at MI-65 to make the transport cart move and lift up-shaft completely remote. Transport of a module by trailer to TSB without a significant coffin will require careful planning, probably including restricting access to roads on the route and full escort. Shielding of the tractor cab will need to be provided to keep dose rates below DOT limits (2 mrem/hr). Storage at TSB of a complete module will also be complicated because of size constraints. The module may need to be rolled on its side to fit within the available headroom. Because of these difficulties, it is greatly desired to succeed with volume reduction methods on component modules or avoid removing modules from the Target Hall entirely.

2.5.15 References[28]

48. "Accelerator-based neutrino beams", Sacha E. Kopp, Submitted to Phys.Rept., http://arxiv.org/PS_cache/physics/pdf/0609/0609129.pdf
49. "The NuMI Technical Design Handbook", http://www-numi.fnal.gov/numwork/tdh/tdh_index.html
50. NuMI Technical Design Handbook, Chapter 4.2.2

[28] Names of References do not necessarily reflect the Proton Plan 2, SNuMI name distinctions.

51. “SNuMI Beam Parameter List”, https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=15
52. “MINOS Experiment and NuMI Beamline”, http://www-numi.fnal.gov
53. "Observation of muon neutrino disappearance with the MINOS detectors in the NuMI neutrino beam," D.G. Michael et al. (273 authors), Fermilab-Pub-06-243, hep-ex/0607088, submitted to Physical Review Letters.
54. “The MINERνA Experiment”, http://minerva.fnal.gov
55. “The NOνA Experiment“, http://www-nova.fnal.gov
56. “NuMI Primary Beam Upgrade for SnuMI“, Sam Childress, https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=30
57. “Dynamic Stress Calculations for ME and LE Targets and Results of Prototyping for the LE Target”, A. Abramov, et. al., IHEP report dated August 10, 2000. NuMI note NuMI-B-675. In this note the width of the target segments is 3.2 mm. The target as built had 6.4 mm wide target segments. (Also SNuMI-doc-92.)
58. (Preliminary) Design Study of the NuMI Medium Energy Target (Task B &C Report of the 2006 Accord between FNAL and IHEP), SNuMI-docdb, https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=78
59. Salman Tariq, ‘Horn 1 Vertical motion in 700 kW operation’, SNuMI-doc-31
60. Salman Tariq, ‘Horn 1 Horizontal motion in 700 kW operation’, SNuMI-doc-45
61. “Temperature and Stresses in the LE Target with 6.4 mm Wide Segments”, IHEP report dated June 20, 2001.
62. Technical Design of the Target Pile Protection Baffle, S.Filippov et al., NuMI-B-1092, April 30, 2002.
63. SNuMI Document 20-v1.
64. K.E. Williams, “MI LCW and Pond Water Temperature Studies”, SNuMI-doc-32.
65. R. Wands, “Qualifying the NuMI Decay Pipe and Hadron Absorber for SNuMI Loads”, SNuMI-doc-81.
66. See Fermilab mechanical drawing ME-363028 Rev. D for layout of the low energy target and horn. The point marked “MCZERO” is the start of the 3 m long idealized horn used of Monte Carlo Simulations.
67. In the PRL letter submitted by MINOS the refer to a “nominal”, “target a 90 cm from nominal”, and a “target 240 cm from nominal” as the configurations corresponding to LE-10, pME, and pHE.
68. Conversation with Peter Lucas.
69. V.Garkusha, A. Ryabov, T. Ryabova, F.Novoskoltsev, V. Zarucheisky “Design Study of the NuMI Low Energy Target (Task A Report of the 2006 Accord between FNAL and IHEP)”, August 30, 2006. https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=18
70. 2006 Accord between IHEP and Fermilab (Task A), https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=17
71. This spacing of the horns comes from NuMI note NuMI-B-1002, IHEP report, “Optimization Studies of Beam Optics for the Low Energy Neutrino Production”, September 10, 2001. This is the same spacing used in the beam sheets in the NuMI Technical Design Report.
72. This is the same spacing used in the beam sheets of the NuMI Technical Design Report.

73. The medium energy target is documented in NuMI-B-675, IHEP report, “Dynamic Stress Calculations for ME and LE Targets and Results of Prototyping for the LE Target.” August 10, 2000.
74. See drawing 7538-00-00-00.dwg for the ME target. (/afs/fnal.gov/files/home/room2/garkusha/ME_target). In this drawing there are 14 graphite plates and the drawing has not been updated to reflect the change to 12 graphite plates. In this drawing there is also a special graphite plate at the downstream end for vertical alignment. The drawing has not been updated with this piece removed.
75. M. Messier, “NOvA Beam Requirements”, SNuMI-doc-91, https://beamdocs.fnal.gov/SNuMI-private/DocDB/ShowDocument?docid=91
76. “Thin Window Under Proton Driver Loads,” R. Wands, 27 Mar 2006.
77. “Qualifying the NuMI Decay Pipe Windows for SNuMi Loads,” R. Wands, presentation given 19 June 2006.
78. “The Numi Decay Pipe Under Proton Driver Loads”, R. Wands, 11 Apr 2005.
79. Abramov, A., et. al., “Advanced Conceptual Design of the NuMI Hadron Beam Absorber Core”, NuMi-B-652, June 30, 2000.
80. “Thermal Stress Analysis of Side-installed NuMI Absorber”, R. Wands, Engineering Report MSG-EAR-01285, 24 April 2001.
81. “Advanced Conceptual Design of the NuMI Hadron Beam Absorber Core”, A.Abramov et al., NuMI Note NUMI-B-652, 30 June 2000.
82. R. Wands, communication via email 9 Aug 2006.
83. N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628 (1995); N.V. Mokhov, O.E. Krivosheev, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000); N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053 (2003); http://www-ap.fnal.gov/MARS/
84. N. Grossman, “Residuals Estimates for SNuMI”, SNuMI Docdb #39.
85. N. Grossman, G. Rameika, “Methodology for Determining Radionuclide Concentration in Groundwater in the Vicinity of Accelerator and Beamline Enclosures”, NuMI Note 970, July 2004.
86. F. Breen, “Evaluation of Boundary Conditions for the Two Dimensional Groundwater Model Simulations, Earth Tech Draft Groundwater Modeling Report, dated, May, 1999”, Technical Memorandum, June 12, 1999; Earth Tech, Inc., “Two Dimensional Groundwater Flow Model, Results Estimated Inflow to NuMI Tunnel”, NuMI Tunnel Modeling Project Report, August 1999; Breen GeoScience Inc., “NuMI 3D Groundwater Model Update”, August 2004.
87. NuMI note 845.
88. See NuMI TDR Chapter 4.2.10 for details.
89. Title 40, *Code of Federal Regulations*, Part 141, “Protection of the Environment”.
90. P. Kesich, J.D. Cossairt, “The Groundwater Monitoring Strategy for NuMI”, NuMI-NOTE-Beam-967, Dec. 2003; ES&H Section, Environmental Protection Team, Environmental Protection Procedures Manual, Procedures 100, 105, 109.
91. “Beams Division Routine Monitoring Program”, BDDP-SH-1003, Rev 0.
92. Kamran Vaziri, “NuMI RAW Systems Containment Plans”, NuMI Note 1009, July 2004.

3 Cost, Schedule, and Scope Range

3.1 Scope

The Work Breakdown Structure (WBS) for Proton Plan 2 is outlined schematically in Table 26. The cost estimate presented in this Section is a very brief summary of the detailed information given in the Proton Plan 2 Plan Resource Loaded Schedule (RLS). It is based on the design described in the earlier Chapters of this Conceptual Design Report. The plan deliverable is the Accelerator Complex and NuMI Beamline ready for commissioning a medium energy neutrino beam for 700kW.

3.2 Cost Range

The Proton Plan 2 Plan consisted of upgrades to existing accelerator and beamline systems or modifications to existing systems to increase proton rate and reliability to the neutrino experimental program. Bottoms up cost estimates were developed by the Proton Plan 2 Level 2 and Level 3 managers in conjunction with people who have done similar work before. It should be noted that these costs are preliminary and physicist labor is not costed in this estimate. The estimates are in Actual Year Dollars (AY$). The cost ranges presented here cover the scope of PP2 which is now part of the NOvA Project (WBS 1.0 and 2.0) as described below.

The Total Estimated Cost (TEC) range is $42 M - $50 M. The Total Project Cost (TPC) range including R&D and operating funding is $55 M - $67 M. The difference between the TPC and the TEC is the R&D and operating funding for the project. The range of the TPC is due to the conceptual nature of some of the upgrades that are needed to existing components or designs. The designs are well established, but the upgrade portions of the designs, especially for NuMI Target Hall components are conceptual since their installation does not occur until near the end of the project.

R&D and operating funds in the amount of $13 - $17 M are requested during FY2007-2011. R&D funds in FY2007 are used to start prototype work on kicker magnet designs. The remaining R&D and operating funds are for design work on magnets, instrumentation, RF, NuMI Target Hall components and infrastructure. This work also includes some beam tests and simulations and moving of existing components in preparation for ANU work. How costs were broken down between MIE, OPC and Off Project is detailed below.

Major Item of Equipment (MIE or TEC portion): tasks that are for procurement, fabrication, testing and installation of new and refurbished equipment for the accelerator and NuMI Upgrades required to support the NOvA Project

Other Project Costs (OPC):

R&D: tasks for prototyping, design and analysis of equipment on the MIE (TEC)

Operating: tasks for non-design and construction activities that don't produce expendable equipment, but are required for the MIE to be successful. These include item such as:

a. Removal of existing equipment in the existing accelerator that is no longer required or will be refurbished.

b. Relocation of existing equipment that will not be refurbished

c. Shielding assessments

Off Project Costs:
Activities that are outside of these definitions have been moved "off-project" since they would be undertaken anyway to provide more reliable, safe, or improved performance of the neutrino program at Fermilab, even if the NOvA Project didn't exist. Included in this category is expendable equipment such as spare parts, magnets, beam tubes, etc. as they produce expendable equipment that would replace existing expendable equipment. Items described in this CDR that are not part of the NOvA Project are:

d. Radioactive component handling, work cell upgrades, and module upgrades

e. Horns and other expendable equipment (spares) required for general operation

f. Civil construction (see following comment)

<u>Civil Construction:</u>
High intensity proton beam operations require extremely fast rise time magnets in the accelerator enclosure and support equipment located externally from the enclosure and proximate to the magnets. The intended purpose of the MI-14 and MI-39 service buildings is to provide a temperature and humidity controlled environment for such support equipment.
The MI-14 building will house the kicker power supply required for injection of protons from the 8 GeV line into the Recycler. The MI-39 building is required to house the new kicker power supply required for full turn extraction of protons from the Recycler to the MI-40 dump, and for the gap clearing kicker required to reduce losses during slip-stacking of protons in the Recycler. Both of these buildings can reasonably be described as "adapting facilities to new or improved production techniques; to affect economy of operations" based on their role in adapting the existing Recycler Ring to its new role as a proton accumulator ring.
In addition a new Anode Power Supply building is proposed for construction outside the MI-60 Service Building. This will house the primary power source supporting the addition of two new RF accelerating cavities in the Main Injector as required to decrease the MI cycle time to 1.33 seconds.
These projects are conceived as benefiting directly the Nova project. However, they will provide improved performance within the ongoing neutrino program even in the absence of Nova. The two kicker buildings are required for any program enhancement that is based on utilization of the Recycler as a proton accumulator ring. Such an enhancement (which requires additional upgrades beyond the two kicker buildings) inherently provides a 50% increase in beam power delivered to the NuMI target independent of the user (MINOS, Minerva, Nova). The new APS building supports an increase in the number of RF accelerating cavities in the Main Injector from 18 to 20. This enhancement inherently provides a 10% increase in the beam power delivered to the NuMI target independent of the user, as well as providing enhanced reliability in Main Injector operations.

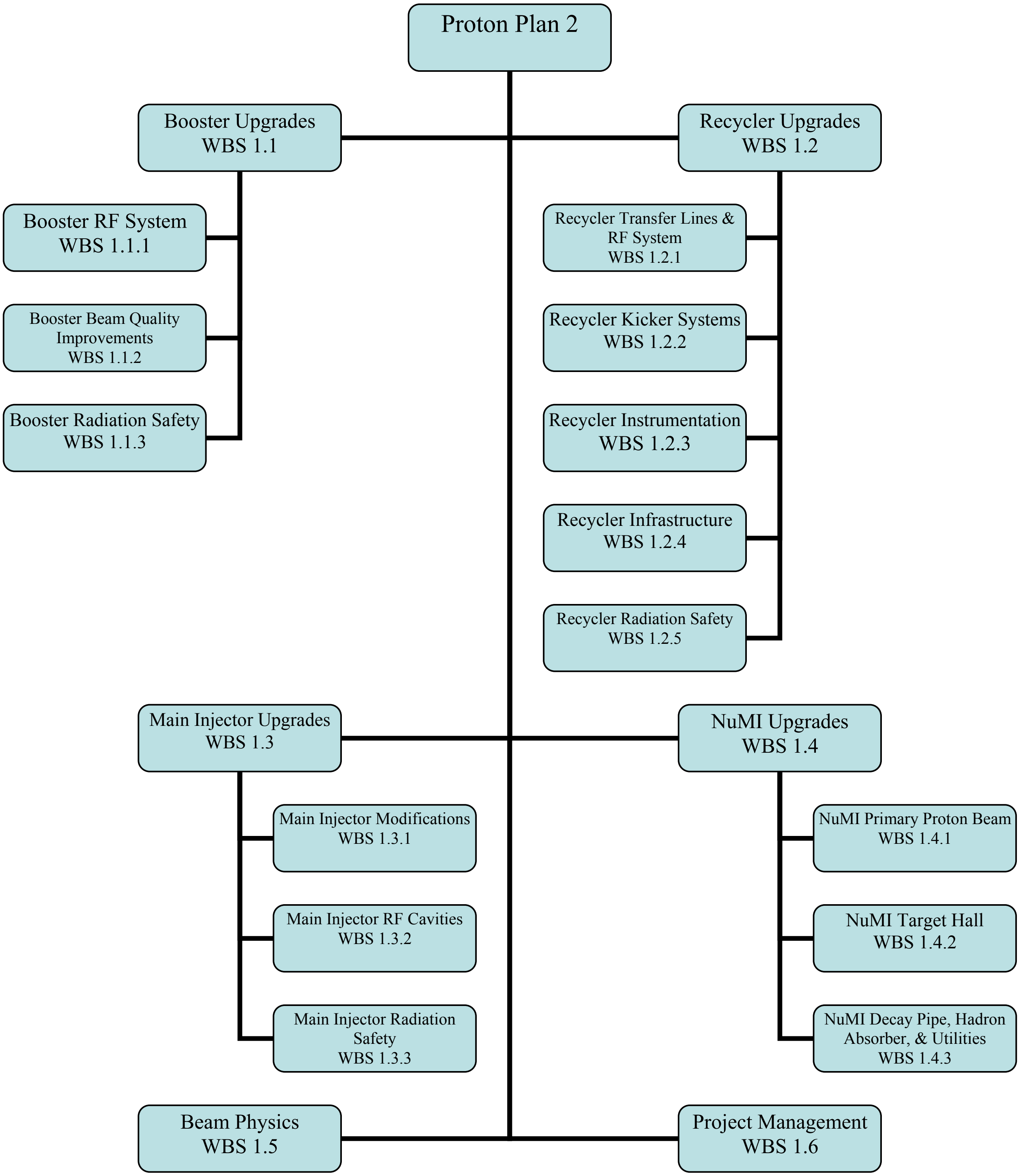
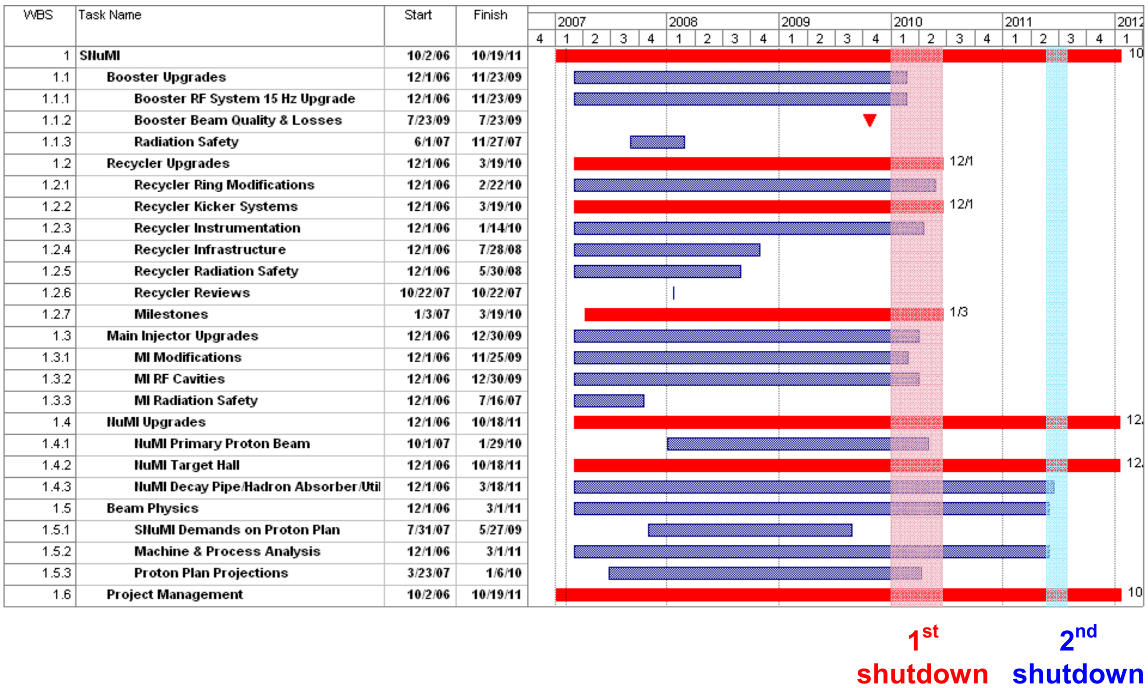


Table 26: Overview of the Proton Plan 2 Work Breakdown Structure, to Level 3

3.3 Schedule Range

The overall project schedule is shown in Table 27. Summary tasks in red have subtasks on the critical path. The summary task durations represent the time from the beginning of the first task to the completion of the last task. Much more detailed schedules are available in the RLS. The Project critical path is shown in Table 28. The critical path is through the Recycler Ring injection kicker system until the end of the 2009 shutdown and then the Horn 1 (and module) installation into the NuMI Target Hall drives the length of the 2011 shutdown. The schedule is largely driven by the shutdown schedules.



WBS	Task Name	Start	Finish
1	SNuMI	10/2/06	10/19/11
1.1	Booster Upgrades	12/1/06	11/23/09
1.1.1	Booster RF System 15 Hz Upgrade	12/1/06	11/23/09
1.1.2	Booster Beam Quality & Losses	7/23/09	7/23/09
1.1.3	Radiation Safety	6/1/07	11/27/07
1.2	Recycler Upgrades	12/1/06	3/19/10
1.2.1	Recycler Ring Modifications	12/1/06	2/22/10
1.2.2	Recycler Kicker Systems	12/1/06	3/19/10
1.2.3	Recycler Instrumentation	12/1/06	1/14/10
1.2.4	Recycler Infrastructure	12/1/06	7/28/08
1.2.5	Recycler Radiation Safety	12/1/06	5/30/08
1.2.6	Recycler Reviews	10/22/07	10/22/07
1.2.7	Milestones	1/3/07	3/19/10
1.3	Main Injector Upgrades	12/1/06	12/30/09
1.3.1	MI Modifications	12/1/06	11/25/09
1.3.2	MI RF Cavities	12/1/06	12/30/09
1.3.3	MI Radiation Safety	12/1/06	7/16/07
1.4	NuMI Upgrades	12/1/06	10/18/11
1.4.1	NuMI Primary Proton Beam	10/1/07	1/29/10
1.4.2	NuMI Target Hall	12/1/06	10/18/11
1.4.3	NuMI Decay Pipe/Hadron Absorber/Util	12/1/06	3/18/11
1.5	Beam Physics	12/1/06	3/1/11
1.5.1	SNuMI Demands on Proton Plan	7/31/07	5/27/09
1.5.2	Machine & Process Analysis	12/1/06	3/1/11
1.5.3	Proton Plan Projections	3/23/07	1/6/10
1.6	Project Management	10/2/06	10/19/11

Table 27: Proton Plan 2 Preliminary Schedule Overview

Uniq	WBS	Name	Dur	St	Fin	Float
1400	1.6.4.1	Approval to Proceed	0d	12/1/06	12/1/06	0d
859	1.4.2.3.1.1	MARs Simulations for Energy Deposition	42d	12/1/06	2/5/07	0d
1001	1.2.2.2.1.1	Design prototype thyratron pulser enclosures (2 variations)	60d	12/1/06	3/1/07	0d
120	1.4.2.3.1.2	FEM 3-D Thermal Analysis	63d	2/6/07	5/3/07	0d
871	1.2.2.2.2.1	RR Injection & Gap Clearing Procure parts & Fluorinert for 2 Pre-production pulsers	80d	3/2/07	6/22/07	0d
645	1.4.2.2.4.1	Analyze stripline (through module to Horn) for higher heat loads.	42d	5/4/07	7/3/07	0d
759	1.4.2.2.4.2	Determine Cooling Needs for Stripline & Remote Joint	0d	7/3/07	7/3/07	0d
888	1.2.2.2.3.1	Assemble Prototype pulsers (2)	30d	6/25/07	8/6/07	0d
646	1.4.2.2.4.3	R&D to develop forced air convection cooling technique for DS "loops" (prototype)	63d	7/5/07	10/2/07	0d
1333	1.4.2.5.10	Module Stripline & Horn Conceptual Design Review	5d	10/3/07	10/9/07	0d
1021	1.2.2.2.3.4	Testing of Prototype Pulsers (2)	60d	8/7/07	10/30/07	0d
1013	1.2.2.1.3.6	High voltage testing 1b of Prototype Magnet	20d	10/31/07	11/27/07	0d
647	1.4.2.2.4.4	Design forced air cooling.	63d	10/10/07	1/14/08	0d
648	1.4.2.2.4.5	Re-design remote joint clamp with water cooling	63d	10/10/07	1/14/08	0d
753	1.4.2.5.3	Stripline & Horn Design Review	5d	1/15/08	1/22/08	0d
877	1.2.2.1.1.4	Revise Prototype Magnet Design & Fab Revised Parts (After 3rd Test)	40d	11/28/07	1/31/08	0d
1018	1.2.2.1.3.11	Pot prototype magnet	20d	2/1/08	2/28/08	0d
1019	1.2.2.1.3.12	Repeat low voltage 4a and high voltage 4b testing of Prototype Magnet	30d	2/29/08	4/10/08	0d
878	1.2.2.1.1.5	Revise Magnet Design for Production & Choose Ferrite (After 4th Test)	20d	4/11/08	5/8/08	0d
1168	1.2.2.1.1.6	Review Final Design of RR Inject Line Kicker Magnet	1d	5/9/08	5/9/08	0d
1078	1.2.2.1.1.7	Decision on Procurement or Re-design of Ferrites	0d	5/9/08	5/9/08	0d
1098	1.2.2.3.2.1	RR Inject & Gap Clearing Prod Kicker Prep Purch Req & Award PO for Ferrites for All Magnets (Sole Source)	40d	5/12/08	7/8/08	0d
952	1.2.2.3.2.2	RR Inject & Gap Clearing Prod Kicker Receive Ferrites for All Magnets	1d	12/30/08	12/30/08	0d
965	1.2.2.3.3.2	Assemble 2 Final Design Magnets & Loads	40d	1/2/09	2/27/09	0d
967	1.2.2.3.3.3	Low voltage testing of 2 Final Magnets	20d	3/2/09	3/27/09	0d
1083	1.2.2.3.1	Decision for Remaining Procurement of Final Design Kicker Magnet Based on Pre-production test	0d	4/24/09	4/24/09	0d
1082	1.2.2.3.3.4	HV Testing of 2 Final Magnets	20d	3/30/09	4/24/09	0d
1037	1.2.2.4.2.5	Procure Thyratrons for 12 Other Pulsers	25d	4/27/09	6/1/09	0d
1271	1.2.2.4.2.9	Prep Purch Req/Issue PO for Parts for 12 Other Pulsers	25d	4/27/09	6/1/09	0d
1273	1.2.2.4.2.6	RR Inject & Gap Clearing Prod Kicker PS Deliver Thyratrons for 12 Other Pulsers	1d	9/23/09	9/23/09	0d
1272	1.2.2.4.2.10	RR Inject & Gap Clearing Prod Kicker PS Deliver Parts for 12 Other Pulsers	1d	9/23/09	9/23/09	0d
1060	1.2.2.4.3.3	Assemble 12 Pulser Housing	60d	9/24/09	12/18/09	0d
1084	1.2.2.4.4	RR Injection & Gap Clearing Checkout Pulsers into Dummy Load	80d	10/22/09	2/19/10	0d
1085	1.2.2.4.5	RR Injection & Gap Clearing Install Magnets & Fluorinert Piping & Checkout 2 Systems	20d	2/22/10	3/19/10	0d
343	1.6.2.6	Finish 2009 Shutdown	0d	3/19/10	3/19/10	0d
1129	1.6.2.7	Start 2011 Shutdown	0d	3/1/11	3/1/11	0d
624	1.4.2.2.1.16	Horn 1 Installation in Chase	20d	3/1/11	3/28/11	0d
644	1.4.2.2.3.9	Horn 1 Module Installation in chase	10d	3/29/11	4/11/11	0d
1130	1.6.2.8	Finish 2011 Shutdown	0d	4/11/11	4/11/11	0d

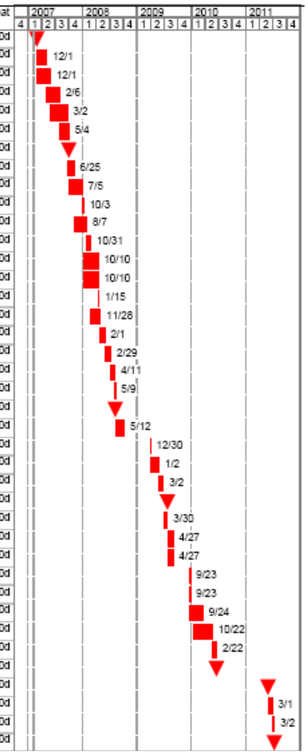


Table 28: Proton Plan 2 Project Preliminary Critical Path

4 Proton Projections

In this section, we estimate the ultimate capability of Proton Plan 2 for providing 120 GeV protons to the neutrino production target. Reasonable ranges of operational parameters are examined to estimate the range of protons deliverable per year, once the upgrades are commissioned. Additionally, we examine the specific case of the 2010 run when Proton Plan 2 is expected to be partially implemented.

4.1 Annual Projections

The annual rates of proton delivery for Proton Plan 2 and SNuMI are based on estimates of beam intensities, efficiencies, and the efficiency/uptime of extended operation. Proton Plan 2 represents the inclusion of the Recycler in the accelerator chain, and associated upgrades throughout; it is described in the rest of this document.

To establish the range of expectations, we consider "design" and "base" scenarios; "design" referring to our expected operating parameters of Proton Plan 2, and "base" referring to a less optimistic set of parameters. The parameters used in the two scenarios are listed in Table 29 and discussed further below[29]. Nominal peak beam power and the annual number of protons delivered are calculated. Our method of estimation is substantially derived from Proton Plan 1 [14].

[29] As a reminder, Phase 1 combines 12 Booster batches in a single beam cycle, Phase 2 combines 18 batches.

	Proton Plan 2		
	Design	Base	
Batch Intensity	4.3×10^{12}	4.0×10^{12}	protons
Cycle Efficiency	0.95	0.9	
Cycle Time	1.333	1.333	seconds
Peak Beam Power	707	623	kW
Complex Uptime	85%	85%	
Avg-to-peak	90%	90%	
NuMI Uptime	80%	70%	
Operating Eff.	61%	54%	
Annual Running Time	44	44	weeks/yr.
Annual Protons	**6.0×10^{20}**	**4.6×10^{20}**	**p/yr.**

Table 29: Assumptions and projections for annually delivered protons when Proton Plan 2 has been fully implemented.

"Batch Intensity" is the number of protons extracted form the Booster per cycle, within the loss limits of the Booster and with requisite beam quality. The predicted intensities are based on current and planned operation in the Booster for slip stacking and NuMI.

"Cycle Efficiency" is the relative proportion of beam delivered at 120 GeV to that extracted from the Booster. For Proton Plan 2, the efficiency goal is 95%, with the losses developing at 8 GeV from the slip stacking process; 90% is typical of present operation, but 95% is the design goal for Proton Plan 1.

"Cycle Time" is the minimum time between 120 GeV extractions. It is achieved through straightforward upgrades, and is not considered to vary.

"Peak Beam Power" is the derived 120 GeV power over one entire cycle. For extended running, this number must be derated for operational efficiencies.

"Complex Uptime" is the long-term portion of time that the accelerator complex is able to provide beam at 120 GeV. Unscheduled shutdowns and component failures of minutes and hours contribute to this operational inefficiency. The values are conservative estimates based on those from Proton Plan 1.

"Avg-to-peak" is a shorter-term value that includes periods of very short downtimes (less than few minutes) and programmatic inefficiencies. The programmatic issues arise from the occasional need to run slow-extraction beam, machine studies, or general complications in arranging an efficient timeline. The value is taken from Proton Plan 1.

"NuMI Uptime" is the long-term portion of time that the NuMI beamline and target station are capable of accepting beam from the Main Injector. This inefficiency is dominated by target and horn failures. The values are derived from operation, but could be substantially increased if more reliable systems are in place.

"Operating Eff." is the product of the three inefficiencies, which are mostly independent.

"Annual Running Time" is a programmatic value that assumes 8 weeks per year are spent on 1 or 2 long shutdowns for general maintenance.

“Annual Protons” is the derived number of protons deliverable at 120 GeV under all of the above assumptions. This number assumes no other major programs require substantial beam or shutdowns. Additionally, the machines are assumed to be fully commissioned.

4.2 2010 MINERvA Run

The initial run of Proton Plan 2 will occur in 2010. At that time the NOvA detector (for which Proton Plan 2 is intended) will still be under construction; however the MINERvA detector (also on the NuMI beam) will be entirely or nearly completed. The MINERvA experiment has requested some portion of their beam exposure (4 x 10^{20} protons) be in the low-energy neutrino configuration of the NuMI target pile. In this section, we estimate the delivery schedule of beam in 2010.

The first Proton Plan 2 shutdown is presently expected to end on March 19, 2010. At the end of that shutdown, the Proton Plan 2 upgrades to the accelerators will be complete, but will not be complete in the NuMI target hall. The delayed target hall upgrades will allow running of low-energy neutrino beam to MINERvA, while the eventual upgrades will require the medium-energy neutrino configuration.

For the purposes of proton projections, we start with the peak beam power derived in the previous section: 623-707 kW (base-design). However, the accelerators will require considerable time for commissioning at the start if this run.

The early running in 2010 will be aided by the ability to inject beam directly to the Main Injector and operate as in Proton Plan 1. Additionally, if slip stacking in the Recycler proves difficult, we may be able to inject beam directly into 300 kV buckets in the Recycler and deliver beam without slip stacking. In the end, we assume commissioning proceeds with a ramp-up time of 12 (design) or 16 (base) weeks. That time is incorporated as t_0 into a simple functional form:

$$P_{Accels} = P_{Max} \times \tanh(t / t_0)$$

Such that at 12 or 16 weeks the power deliverable by the accelerators is 76% of the eventual peak beam power.

The low-energy neutrino configuration will not be able to accept the full beam power deliverable by the accelerators after the Proton Plan 2 upgrades. The more aggressive target design and close proximity of Horn 1 will limit the beam power to 400 (base) or 480 (design) kW. The eventual limit will be determined by studies of the components, and decisions on whether short-term cooling options should be explored. The actual peak beam power delivered to the NuMI target (during the 2010 run) is then taken as the minimum of that deliverable by the accelerators or the limit set by the target station.

The actual peak beam power is then multiplied by the operational efficiency, from the previous section, and integrated to produce the predictions in Figure 72. The plot is calculated assuming no further long planned shutdown until the 4 x 10^{20} protons are delivered; actually, Proton Plan 2 installations or program planning may require a shutdown earlier.

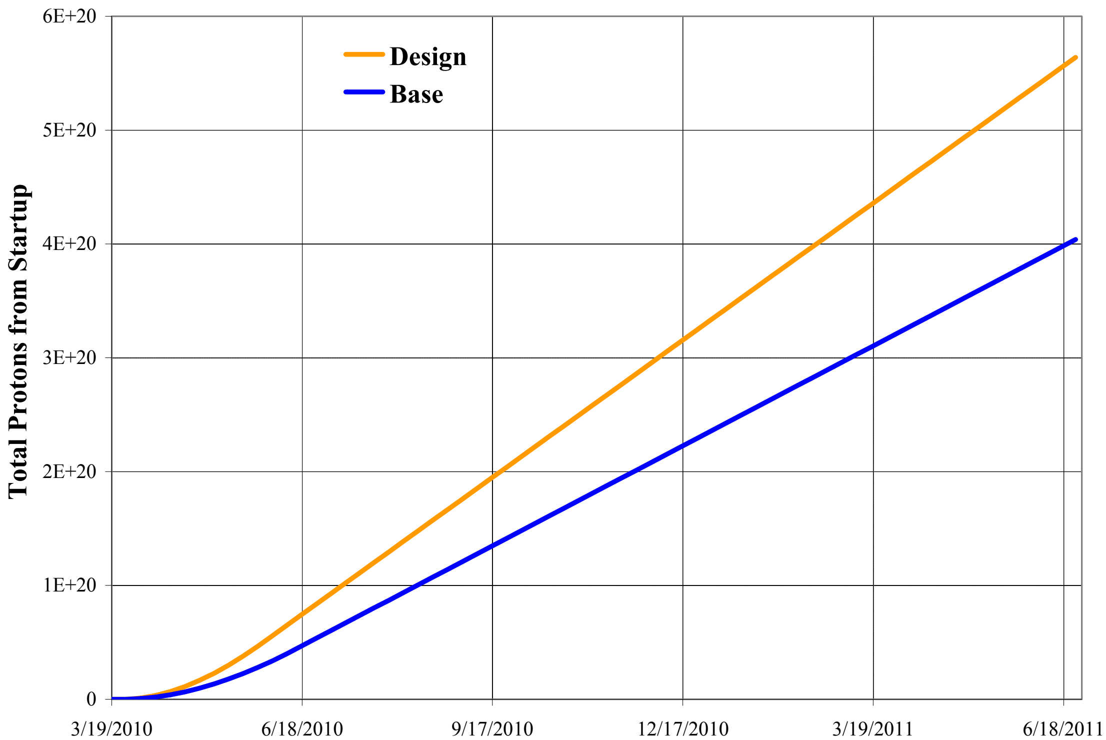


Figure 72: Projected number of protons delivered to the neutrino production target in the 2010 run when the Proton Plan 2 upgrades are partially implemented and MINERvA is the primary user.

The time to accumulate 4 x 10^{20} protons is 338 days in the design scenario and 458 days in the base scenario. The corresponding dates are February 2, 2011 and June 20, 2011.

4.3 References

93. D. McGinnis, "A 2 MW multi-stage proton accumulator", FNAL-Beams-doc-1782, 2005.

94. The Proton Plan Design Handbook (Phase I) is found on its webpage: http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.shtml. A public site viewable outside Fermilab is: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml